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THREE DIMENSIONAL MICROPROCESSOR CONTROLLED MICRO-MANIPULATOR SYSTEM

by

© JUGDUTT SINGH

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE
OF MASTER OF SCIENCE

DEPARTMENT OF ELECTRICAL ENGINEERING

EDMONTON, ALBERTA
FALL 1986

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Date: 25th June, 1986.

THE UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled **Three Dimensional Microprocessor Controlled Micro-Manipulator System**, submitted by **Jugdutt Singh** in partial fulfilment of the requirements for the degree of **Master of Science**.

....
(Supervisor)

Roger W. Toogood

Keith A. Stromsmoe

....

....

Date: 25 June 1986

DEDICATION

To my wife, Mohini and sons
Deepak and Amrish for their love and
encouragement in all my endeavors.

ABSTRACT

The requirement, design and performance of a microprocessor controlled micro-manipulator system are described. The system is designed to minimize the time required to position the microelectrode and to obtain successful microelectrode measurement from smooth muscle tissue of the gastrointestinal tract. The three dimensional microprocessor controlled micro-manipulator system is designed using a Motorola MC6809 microprocessor and associated serial and parallel interface circuits. The microelectrode position in the "X", "Y" and "Z" directions is controlled by the three dimensional hydraulic manipulator. The hydraulic link is used between the manipulator with microelectrode holder and the stepper motor arrangement to overcome vibration caused by the stepper motors and micrometer arrangement. This also isolates the user from the vibration sensitive measurement.

The displacement produced by the "X", "Y" and "Z" stepper motors produces proportionally linear displacement of the fluid in the hydraulic chamber which in turn causes proportional linear position change of the microelectrode in the "X", "Y" and "Z" direction. The system is controlled by a three dimensional joystick.

Additional features of the system include the control of the manipulator via a keyboard, features like automatic Return to Home Position, automatic stoppage of tissue penetration once the minimum intracellular threshold voltage is reached, flexibility in altering the input parameters and a variable stepper motor stepping rate.

This system is intended to aid biomedical research at the University of Alberta. Consequently, there is an emphasis on reliability and ease of operation.

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I owe a debt of gratitude to my wife, Mrs. Mohini Singh for her encouragement, patience and understanding during my course of study. This work would not have been possible without the patience of my children, Deepak and Amrish.

I wish to thank the Canadian Commonwealth Scholarship and Fellowship Committee and the Government of Fiji for providing me with financial support and in-service-training during the course of the work.

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CHAPTER 1

INTRODUCTION

Measurement of electrical potentials inside living cells is accomplished using microelectrodes made from glass capillary tubing which has been heated and pulled to obtain a capillary which has a diameter of one micron or less. The capillary is filled with three molar potassium-chloride solution, KCl, inserted into the holder and connected via a silver-silverchloride pellet to a very high impedance amplifier [21]. The impedance of the microelectrode is of the order of 100 Megaohms. Using a precision three-dimensional manipulator the microelectrode is positioned such that it penetrates a cell of the tissue specimen inserted in a nutrient solution in a tissue perfusion system.

The degree of difficulty associated with obtaining a microelectrode measurement is inversely proportional to the size of the cell upon which measurement is being carried out. The smaller the cell the smaller the fraction of measurements which are successful. The smooth muscle cells of interest in this particular work are typically two to four microns in diameter and two hundred microns in length.

The development of a three-dimensional microprocessor controlled micro-manipulator system has been motivated by the need to minimize the time required to successfully position the microelectrode to the desired position and to obtain successful microelectrode measurements from a smooth muscle tissue of the gastrointestinal tract. By closely observing the different types of electrical and mechanical activity and the conditions under which the activity occurs, insight into the mechanisms and functions of the gastrointestinal tract may be obtained.

The position of the microelectrode in the "X", "Y" and "Z" directions is controlled by the three stepper motors, one for each direction. The Joystick inputs are digitised using an Analog-Processing module. The number of steps that the stepper motors take and the direction of rotation of the stepper motors are determined by the Joystick setting.

The three stepper motors are hydraulically linked to the three dimensional hydraulically controlled manipulator which positions the microelectrode holder. Any steps taken by the stepper motors will produce proportional linear displacement of the manipulator in any or all of the three directions.

The stepper motors control algorithm is such that if the number of steps to be taken by the stepper motors are large the motors will accelerate/decelerate to within a few microns of the desired position and then rotate with constant velocity for the remaining few microns [3,41,60]. This arrangement will thus save valuable time. The stepper motors control parameters can also be entered via keyboard.

CHAPTER II

SYSTEM DESCRIPTION

The complete block diagram of the three dimensional microprocessor controlled micro-manipulator system is shown in figure II.1. This system utilizes open-loop control of stepping motors for controlling the position of the microelectrode. The system consists of:

(i) A Microcomputer System
(ii) Stepper Motor Control Circuitry
(iii) An Analog Processing Module
(iv) Keyboard and Display Modules
(v) An Output Module

The microcomputer utilizes a Motorola MC6809 microprocessor working at 1MHz clock frequency. The stepper motor control circuitry consists of Parallel Interface Adaptors (PIAs) and transistor drivers. Each of the three stepper motors are controlled by the four output lines on the "B" side of two Parallel Interface Adaptors. These lines are pulsed in sequence to cause the motors to turn either clockwise or in a counterclockwise direction. The motors speeds are controlled by the rate at which the motors are pulsed.

The three stepper motors are connected via precision non-rotating spindle micrometers to the hydraulic controlled three dimensional manipulator to control the position of the microelectrode. With this system the microelectrode can be positioned to within 0.5 microns. A Joystick is used to input position information to the stepper motors.

Control parameters can also be input to the system via a 4x4

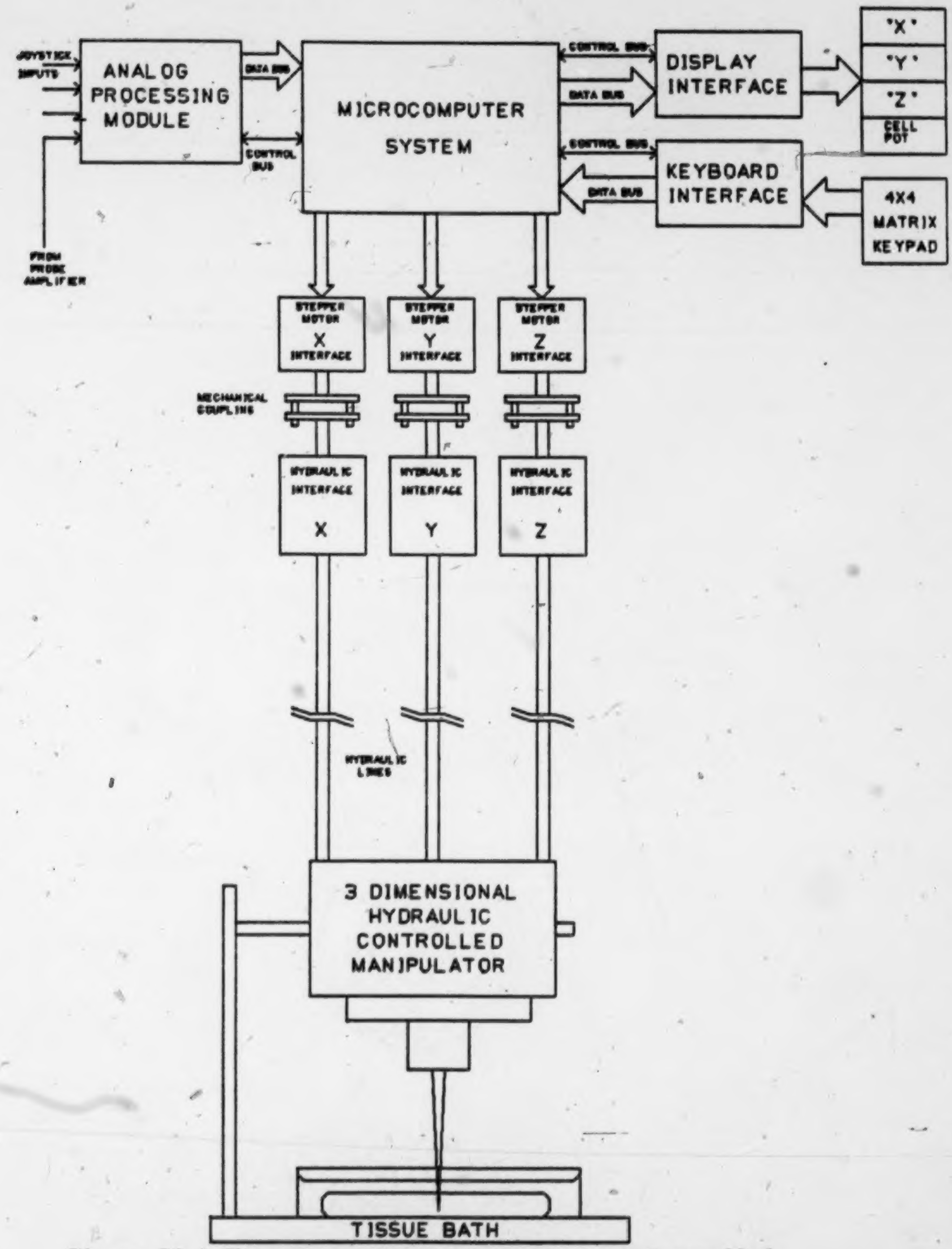

JOYSTICK INPUTS
ANALOG PROCESSING MODULE
DATA BUS
CONTROL BUS
MICROCOMPUTER SYSTEM
CONTROL BUS
DATA BUS
DISPLAY INTERFACE
"X"
"Y"
"Z"
CELL POT
CONTROL BUS
DATA BUS
KEYBOARD INTERFACE
4X4 MATRIX KEYPAD
FROM PROBE AMPLIFIER
STEPPER MOTOR X INTERFACE
STEPPER MOTOR Y INTERFACE
STEPPER MOTOR Z INTERFACE
MECHANICAL COUPLING
HYDRAULIC INTERFACE X
HYDRAULIC INTERFACE Y
HYDRAULIC INTERFACE Z
HYDRAULIC LINES
3 DIMENSIONAL HYDRAULIC CONTROLLED MANIPULATOR
TISSUE BATH

Figure II.1 Three Dimensional Microprocessor Controlled Micro-Manipulator System

matrix keyboard. The keyboard is interfaced to the microcomputer via a keyboard encoder. The main input functions are:

(i) Set V_{THMIN} (Minimum Intercellular Threshold Potential)
(ii) Digits 0-9
(iii) Set "X" position of the microelectrode
(iv) Set "Y" position of the microelectrode
(v) Set "Z" position of the microelectrode
(vi) "Home" and "Go" controls
(vii) "Enter" and "Clear" facilities

Keyboard entry enables the user to quickly position the microelectrode to any desired position. this mode disables the Joystick control mode which is used for the final few micron positioning of the microelectrode.

The display consists of four rows of four digits of seven segment light emitting diode displays with fixed decimal point. The display is controlled using two Intersil ICM7218 display drivers. The parameters normally displayed are:

(i) the "X" position of the microelectrode
(ii) the "Y" position of the microelectrode
(iii) the "Z" position of the microelectrode
(iv) intracellular potential

Another function of the system is the monitoring of the microelectrode signal (potential) via channel four of the analog processing module. This signal is compared to the set threshold levels and used to stop advancement of the microelectrode when the required signal level is obtained.

CHAPTER III

SYSTEM REQUIREMENTS

The requirements of the three dimensional microprocessor controlled micro-manipulator system are to perform the control of the position of the microelectrode to within 0.5 microns, display the position of the microelectrode in the "X", "Y" and "Z" directions with reliability and ease. As the system is to be used in the medical laboratory environment, it must be easy to operate, allowing the user to fully concentrate on other aspects of his research. The system design must be such that vibration has minimal effect on the position of the microelectrode. It is desirable that the system be as flexible as possible, to maximize its possible applications.

III.1 MICROCOMPUTER SYSTEM

The central device to the system is required to control and execute the functions of acquiring and processing data, controlling the three stepper motors and displaying position of the microelectrode in "X", "Y" and "Z" directions. The microcomputer can be selected and constructed to give maximum reliability. Software should be written with particular attention to efficiency and it should be structured to provide reliability and to provide ease of future software expansion.

A three-dimensional micro-manipulator system based on a dedicated microcomputer will be easier to operate.

III.2 DATA ACQUISITION AND DISPLAY

In this system two types of data must be acquired. One type of data is the sampled analog signal from the "X", "Y" and "Z" controls of the joystick and the microelectrode amplifier. The other type of data consists of precise descriptions of the microelectrode position, threshold voltage and other manipulator control parameters. The descriptive data must be entered by the operator. It is the function of the Analog Processing Module to obtain the sampled data from the joystick and microelectrode amplifier. The system should display the "X", "Y" and "Z" co-ordinates of the microelectrode. The maximum deflection will be 128 microns with a minimal resolution of 0.5 microns. Thus, display of the "X", "Y" and "Z" co-ordinates will require four digits. It is also required to monitor the microelectrode cell potential.

III.3 THE OUTPUT MODULE

The output module is a mechanical system consisting of a three-dimensional manipulator with microelectrode holder and the stepper motor interface to a hydraulic system. This system consists of two miniature bellows coupled by a fluid filled polyethlyene tube. As the stepper motor increment is 7.5°, it is required that a step increment be converted to 0.5 micron displacement of the microelectrode attached to the three dimensional manipulator. Since energizing the stepper motors and other mechanical devices will cause excessive vibration, it is also required that any vibration caused by the system to have no effect on the microelectrode position.

III.4 CONTROL

A control device in the three-dimensional micro-manipulator system is required to allow the user to define the operation of the data acquisition system and the output module. As this device is the interface between the user and the system, it should prevent the user from making incompatible requests, provide some guidance when the user makes an error, and provide an acknowledge when the request is granted.

A keyboard used to control system operation, and displays and beepers used to indicate status, can be mounted on the front panel. This would allow for quick and simple system control.

CHAPTER IV

SPECIFICATION

Once the general functions and requirements of the three dimensional micro-manipulator system have been considered, one can select or specify the major components or operations necessary to realize those requirements.

IV.1 MICROCOMPUTER SYSTEM

As a dedicated microcomputer system is required, a microcomputer based on the Motorola MC6809 was chosen. This choice was based on the software development support available for this microprocessor at the University. The most significant factor in making this choice was the availability of the Motorola MC6809 Cross Assembler. Other considerations were the availability of the Motorola MC6809 based system components and a familiarity with this particular processor.

IV.2 DATA ACQUISITION AND DISPLAY

As outlined by the requirements section, the functions that must be performed by this module are sampling data from the three dimensional joystick and the microelectrode amplifier, displaying the position of the microelectrode in the "X", "Y" and "Z" plane (X,Y and Z co-ordinates) with respect to the predetermined reference and monitoring and displaying the intracellular potential.

The devices selected for data sampling are an eight bit analog to digital converter, eight-to-one analog multiplexer connecting the joystick inputs, the microelectrode amplifier and the associated sequence generator circuitry. The multiplexed system is chosen as it is cheaper when compared to a parallel data acquisition system. The data is sampled continuously and stored in memory for further processing and control of the stepper motors.

The display system chosen consists of seven-segment common anode displays for "X", "Y" and "Z" co-ordinates and the intracellular potential. Each display consists of four digits as the maximum deflection of the microelectrode is 128 microns with the resolution of 0.5 microns. Separate "X", "Y" and "Z" position displays are chosen to ensure that the microelectrode position in "X", "Y" and "Z" directions are continuously displayed.

IV.3 THE OUTPUT MODULE

The functions of the output module are to interface the stepper motors to the three master bellows, to provide three dimensional motion of the microelectrode and to isolate the three dimensional manipulator to which the microelectrode is attached from any vibration caused by the system or external sources. The high precision non-rotating spindle micrometer arrangement is used to interface the stepper motor to the master bellows. This arrangement converts the circular motion of the stepper motors to linear displacement suitable for the control of the bellows. The master bellows are attached to the slave bellows, which are attached to the three dimensional manipulator, via a polyethylene tubing. The micrometer resolution and master and slave bellows diameters are chosen to give the required resolution in the displacement of the microelectrode attached to the three dimensional manipulator.

IV.4 CONTROL

A number of control functions are provided to allow the user to specify or manipulate the operation of the three-dimensional micromanipulator system. The operator is able to control the position of the microelectrode by entering the desired position in either ""X", "Y" or "Z" direction via the keyboard. The operator is also able to alter the cell threshold voltage. The system also allows the user to cause the microelectrode to return to "Home" position by depressing the "Home" key. The system also has a built in feature which automatically stops the microelectrode penetration once the microelectrode has entered the cell (intracellular potential<cell threshold voltage). Further penetration into the tissue can be achieved by depressing Forced Penetration key. The system also has LED displays to indicate whether the system is in joystick mode, keyboard mode, "Home" position or standby position. On servicing the keyboard mode routine the system returns to the "stand-by" mode, indicated by flicking LED display, until the "Go" key is pressed.

CHAPTER V

IMPLEMENTATION

V.1 HARDWARE

The complete three dimensional microprocessor controlled micromanipulator system consists of:

(i) The microcomputer and interface used for software development.

(ii) The stepper motor control circuitry.

(iii) The analog processing module.

(iv) The keyboard input and the display system.

(v) The output module consisting of hydraulic interface and precision three dimensional manipulator with electrode holder.

The complete system is constructed on two circuit boards. The first board contains the microprocessor with its associated integrated circuitry and the joystick interface. The second board contains the keyboard interface, display interface, stepper motors interface, the microelectrode voltage interface and LED and beeper interface.

V.1.1 MICROCOMPUTER SYSTEM

The dedicated microcomputer system [21,42,46,62] is based on a Motorola MC6809 microprocessor working at 1MHz clock frequency. The block diagram of the microcomputer system is shown in Figure V.1. The microcomputer system board has been wire wrapped to provide high component densities, rapid construction and a means to easily modify circuitry.

To avoid accidental activation several control lines on the Motorola MC6809 microprocessor are pulled up to V_{CC} through pull up

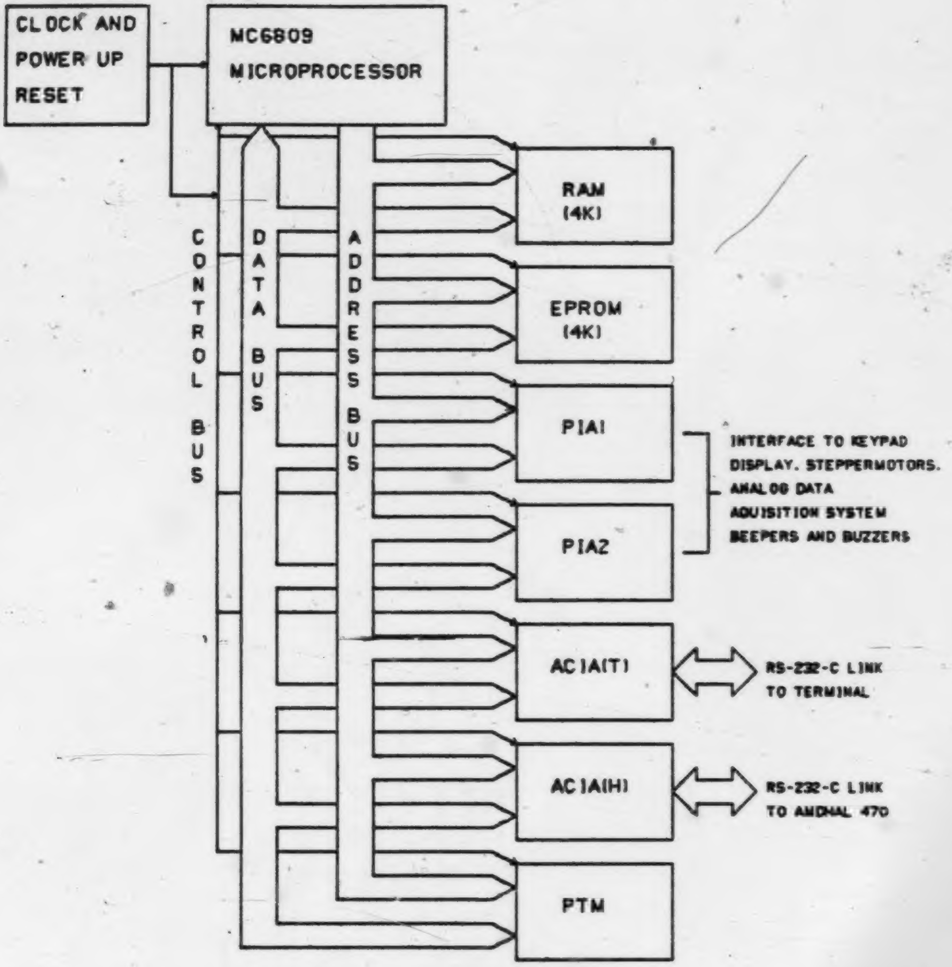

CLOCK AND POWER UP RESET
MC6809 MICROPROCESSOR
CONTROL BUS
DATA BUS
ADDRESS BUS
RAM (4K)
EPROM (4K)
PIA1
PIA2
ACIA(T)
ACIA(H)
PTM
INTERFACE TO KEYPAD DISPLAY. STEPPERMOTORS. ANALOG DATA AQUISITION SYSTEM BEEPERS AND BUZZERS
RS-232-C LINK TO TERMINAL
RS-232-C LINK TO AMDHAL 470

Figure V.1 The Microcomputer System

resistors as shown in Figure V.2. These lines are MRDY(36), NMI(2), FIRQ(4), IRQ(3), HALT(40), BREQ/DMA(33) and RESET(37).

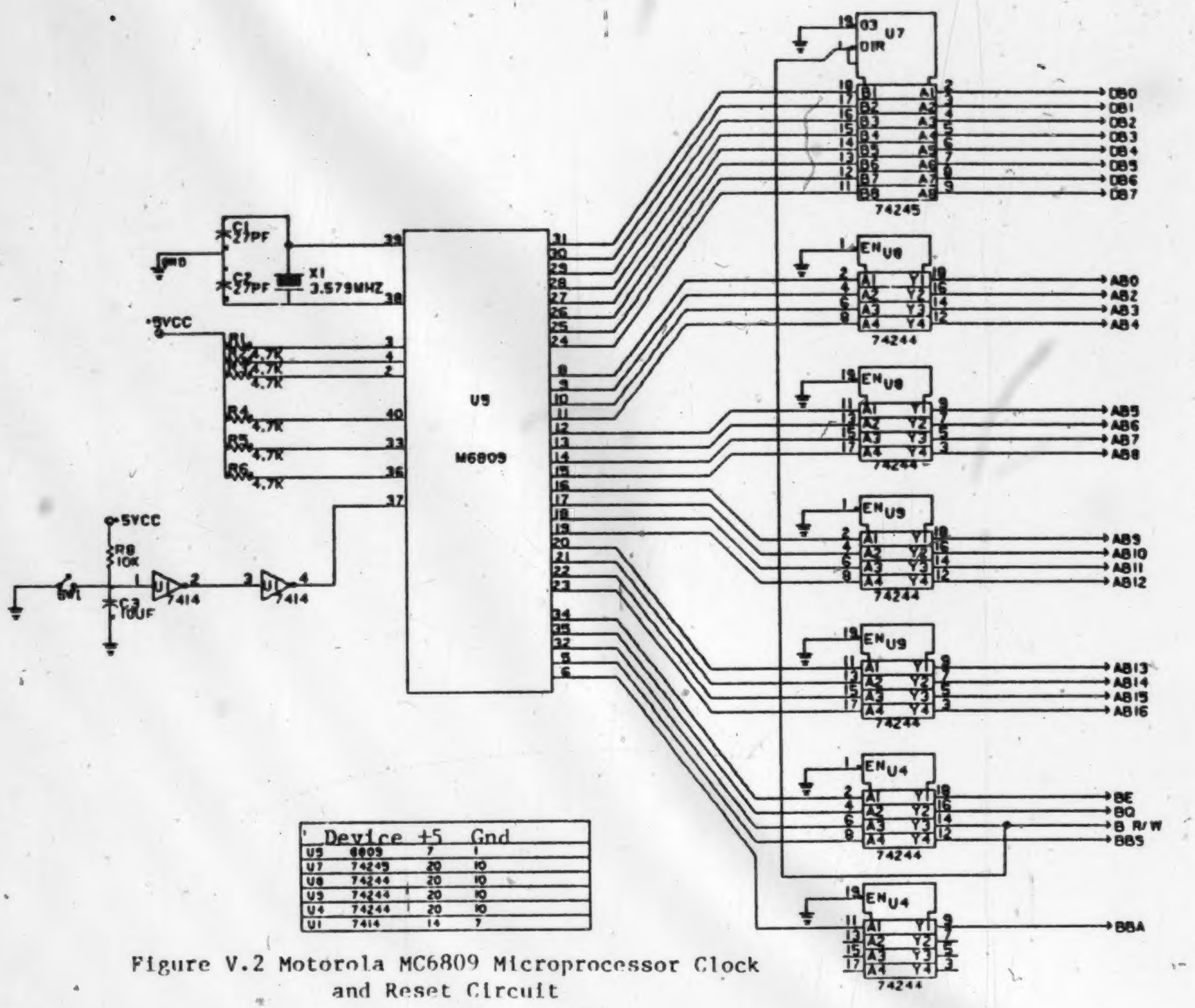
A power ON reset circuit is also connected to the reset pin. On power up the capacitor holds the line low long enough for the reset to take place.

The regular interrupt line (IRQ) is wire-ored to the Asynchronous Communication Interface Adaptors (ACIA's), the Programmable Timer (PTM) and the Parallel Interface Adaptors (P1A1 and P1A2).

As the Motorola MC6809 microprocessor has no on-chip buffering, all the address, control and data lines are buffered to provide the required current drive. SN74LS244 octal buffers are used for buffering address and control lines. Since the data lines are bidirectional, SN74LS245 octal bus transceivers with directional control provided by the $R/\overline{W}$ line are used.

The buffered address lines A12-A15 and SN74154 4-line to 16-line decoder/demultiplexer are used to break the 64 Kilobyte address space into 4 Kilobyte blocks. The detailed decoder circuit is shown in Figure V.3.

Two Motorola Asynchronous Communication Interface Adaptors MC6850 (AC1A's) are used to create serial RS-232-C ports originally connected to the terminal and a Amdahl 470 host computer. A Motorola MC6809 debug monitor program facilitated communication between the terminal and the host. All software was developed using the Motorola MC6809 Cross-Assembler running on the Amdahl 470 computer. The two ports remain on the system to permit future upgrading or debugging of the software. The detailed connection of the two Asynchronous


C1 27PF
C2 27PF
X1 3.579MHZ
5VCC
R1
R2 4.7K
R3 4.7K
4.7K
R4 4.7K
R5 4.7K
R6 4.7K
5VCC
R8 10K
C3 10UF
SW1
U1 7414
U1 7414
U5
M6809
U7
DIR
74245
EN U8
74244
EN U9
74244
EN U4
74244
DB0
DB1
DB2
DB3
DB4
DB5
DB6
DB7
AB0
AB2
AB3
AB4
AB5
AB6
AB7
AB8
AB9
AB10
AB11
AB12
AB13
AB14
AB15
AB16
BE
BQ
B R/W
BBS
BBA

Device		+5	Gnd
U5	6809	7	1
U7	74245	20	10
U8	74244	20	10
U9	74244	20	10
U4	74244	20	10
U1	7414	14	7

Figure V.2 Motorola MC6809 Microprocessor Clock and Reset Circuit

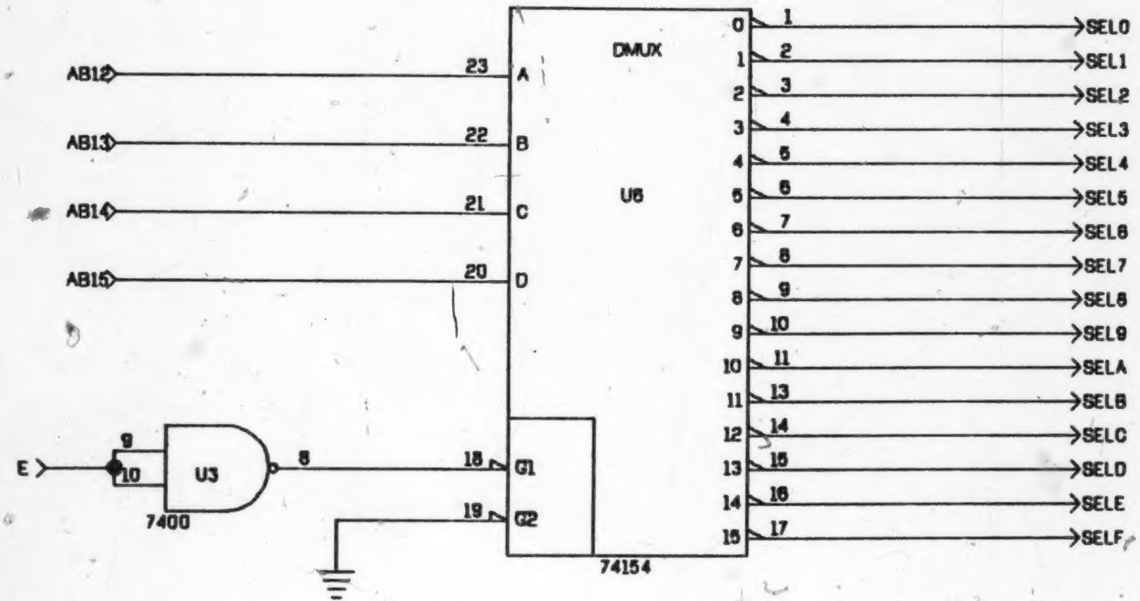

AB12
AB13
AB14
AB15
E
23
22
21
20
A
B
C
D
9
10
U3
7400
8
18
19
G1
G2
DMUX
U6
74154
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
1
2
3
4
5
6
7
8
9
10
11
13
14
15
16
17
SEL0
SEL1
SEL2
SEL3
SEL4
SEL5
SEL6
SEL7
SEL8
SEL9
SELA
SELB
SELC
SELD
SELE
SELF

Figure V.3 Microcomputer System-Memory Decoder

REFDES	DEVICE	+5V	GND	-5V	-8V
U6	74154	24	12		
U3	7400	14	7		

Communication Interface Adaptors (HOST and TERMINAL ACIA) to the microprocessor unit is shown in Figure V.4.

The system software is contained in two, 2 Kilobyte MCM2716 EPROMs connected at address locations $F000 and $F800 respectively.

The system random access memory (RAM) consists of two, 2 Kilobyte x 8 CMOS 6116 RAMS. These RAMS reside at memory location $D000 and $D800. The detailed RAM and EPROM circuit connections are shown in Figure V.5, and Figure V.6 respectively.

Two Motorola MC6821 Parallel Interface Adaptors (PIA1 and PIA2) are used to provide universal means of interfacing peripheral equipment to the Motorola MC6809 microprocessing unit. This device is capable of interfacing the microprocessing unit to the peripherals through two eight-bit bidirectional peripheral data buses and four control lines. The functional configuration of the Parallel Interface Adaptor is programmed by the microprocessor during system initialisation. In this microcomputer system the Parallel Interface Adaptor 1 (PIA1) is connected at address location $8000 and the Parallel Interface Adaptor 2 (PIA2) is connected at address location $9000. Parallel Interface Adaptor 1(PIA1) data lines are programmed to make Port A data lines PA0-PA3 act as input lines from the 4x4 matrix keyboard and PA4-PA7 to act as output lines to the LED displays and resetting the analog processing module. Port B is programmed to act as Output Port to control stepper motors "X" and "Y". Similarly Parallel Interface Adaptor 2 (PIA2) data lines are programmed to make Port A to act as input port to interface the analog processing module and the Port B to act as Output port to control stepper Motor "Z" displays,beepers and to

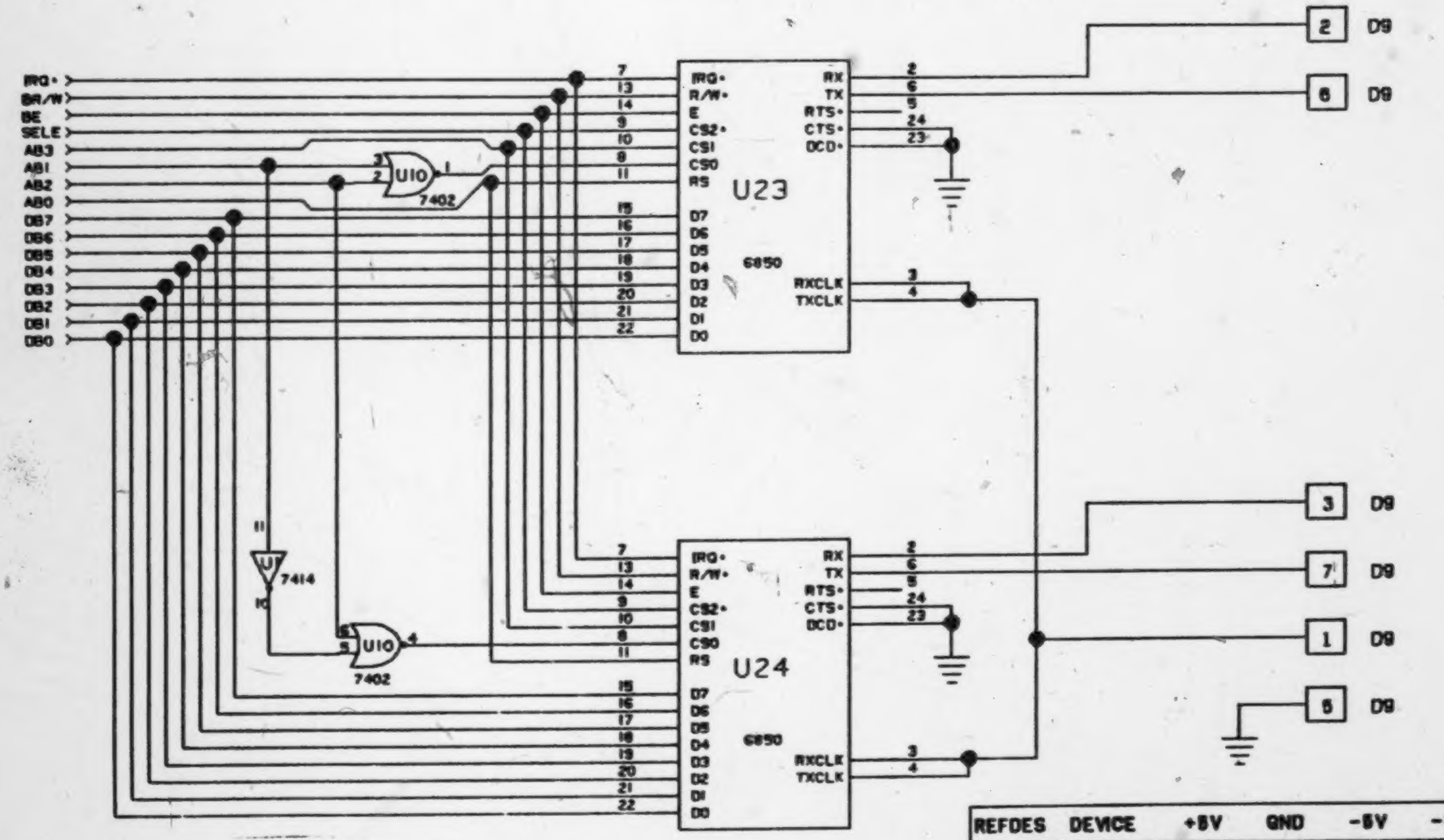

IRQ•
BR/W
BE
SELE
AB3
AB1
AB2
AB0
DB7
DB6
DB5
DB4
DB3
DB2
DB1
DB0
U10
7402
U1
7414
U23
6850
U24
6850
IRQ•
R/W•
E
CS2•
CS1
CS0
RS
D7
D6
D5
D4
D3
D2
D1
D0
RX
TX
RTS•
CTS•
DCD•
RXCLK
TXCLK
2
6
3
7
1
5
D9

Figure V.4 Microcomputer System - Asynchronous Communication Interface Adaptor

REFDES	DEVICE	+5V	GND	-5V	-8V
U5	7402	14	7		
U23	6850	12	1		
U24	6850	12	1		
U6	7414	14	7		

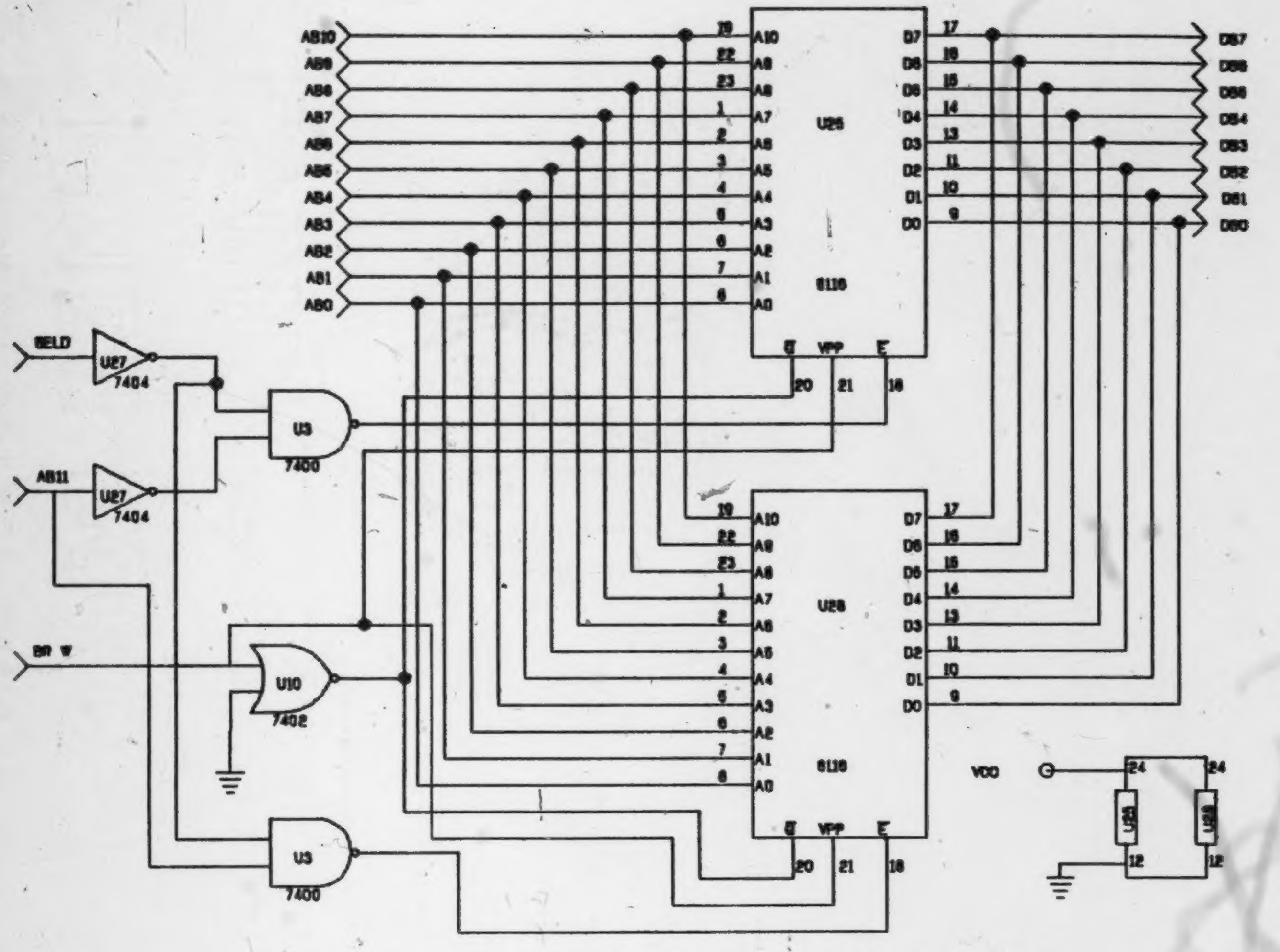
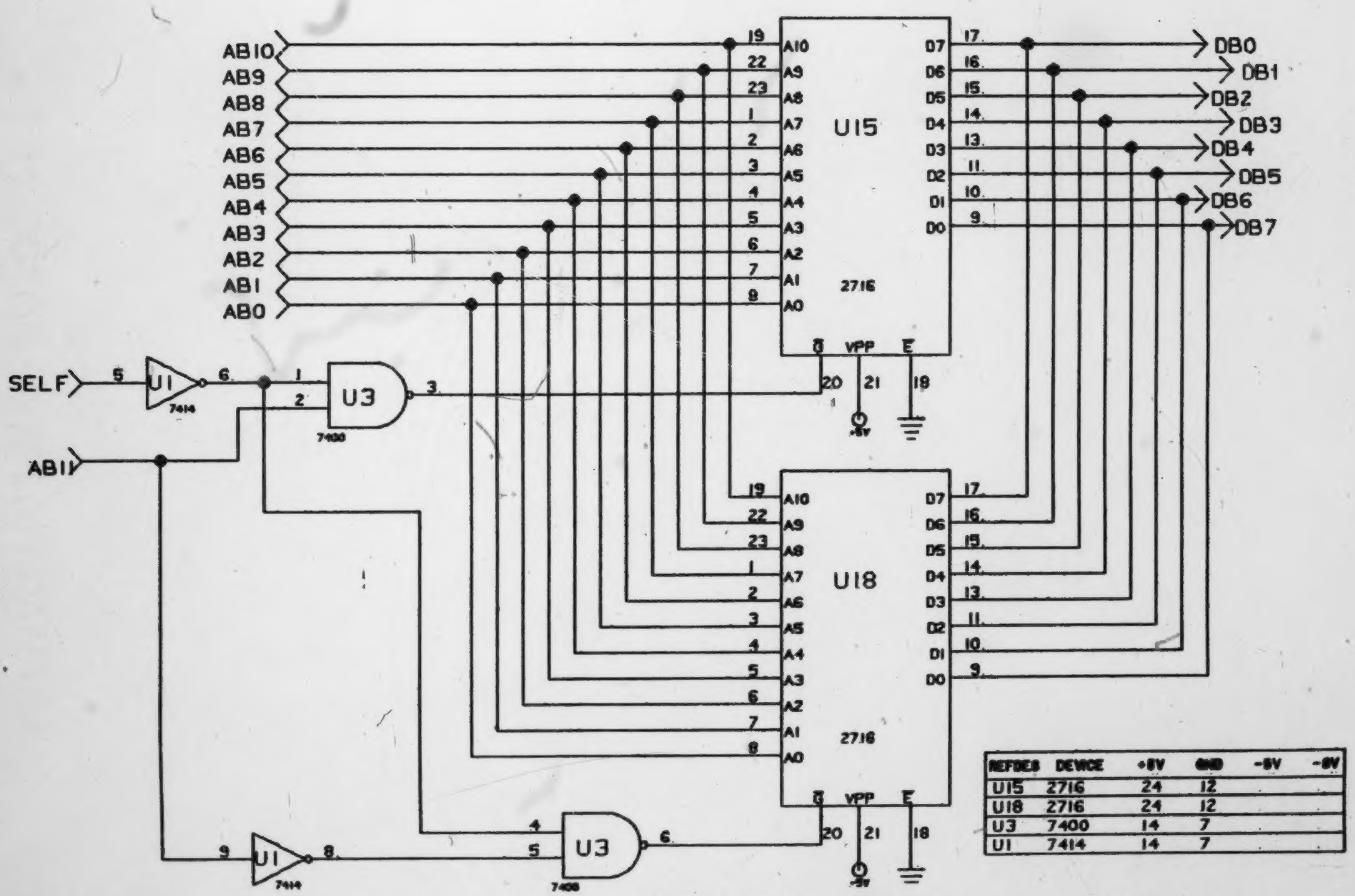

AB10
AB9
AB8
AB7
AB6
AB5
AB4
AB3
AB2
AB1
AB0
SELD
AB11
BR W
U27
7404
U27
7404
U3
7400
U10
7402
U3
7400
U25
6116
U26
6116
A10
A9
A8
A7
A6
A5
A4
A3
A2
A1
A0
D7
D6
D5
D4
D3
D2
D1
D0
G
VPP
E
20
21
18
DB7
DB6
DB5
DB4
DB3
DB2
DB1
DB0
VCC
24
12

Figure V.5 Microcomputer System - 4 Kilobyte Memory


AB10
AB9
AB8
AB7
AB6
AB5
AB4
AB3
AB2
AB1
AB0
SELF
AB11
U1
7414
U3
7400
U15
U18
2716
A10
A9
A8
A7
A6
A5
A4
A3
A2
A1
A0
D7
D6
D5
D4
D3
D2
D1
D0
G
VPP
E
+5V
DB0
DB1
DB2
DB3
DB4
DB5
DB6
DB7

REFDES	DEVICE	+5V	GND	-5V	-5V
U15	2716	24	12	.	.
U18	2716	24	12	.	.
U3	7400	14	7	.	.
U1	7414	14	7	.	.

Figure V.6 Microcomputer System - 4 Kilobyte EPROM

provide a clock interface for the analog-processing-module. Figure V.7 shows the detailed circuitry of the Parallel Interface Adaptors.

The system also contains a Motorola Programmable Timer MC6840 (PTM) connected at address location $E000. The Programmable Timer has three 16 bit binary counters, three corresponding control registers and a status register. These counters are under software control and are used to cause system interrupts during software development. Figure V.8 shows the detailed Programmable Timer module circuitry.

V.1.2 STEPPER MOTOR CONTROL

The essential property of the stepping motor is its ability to translate switched excitation changes into precisely defined increments of rotor position ("steps"). Accurate positioning of the rotor is generally achieved by magnetic alignment of the iron teeth on the stationary and rotating parts of the motor.

Stepping motors are most often used in position control applications without expensive feedback loops. This driving method is referred to as open-loop drive [36].

Though open loop control is an economically advantageous driving method, there are limitations. For example the motor becomes oscillatory and unstable in certain speed ranges and due to this behavioural characteristic, the speed and acceleration of a stepping motor controlled in the open-loop scheme cannot be as fast as D.C. motor driven in feedback control scheme.

V.1.2.1 PERMANENT MAGNET STEPPING MOTORS

A stepping motor using a permanent magnetic in the rotor is called a permanent magnet (PM) motor. An example of a basic four-phase

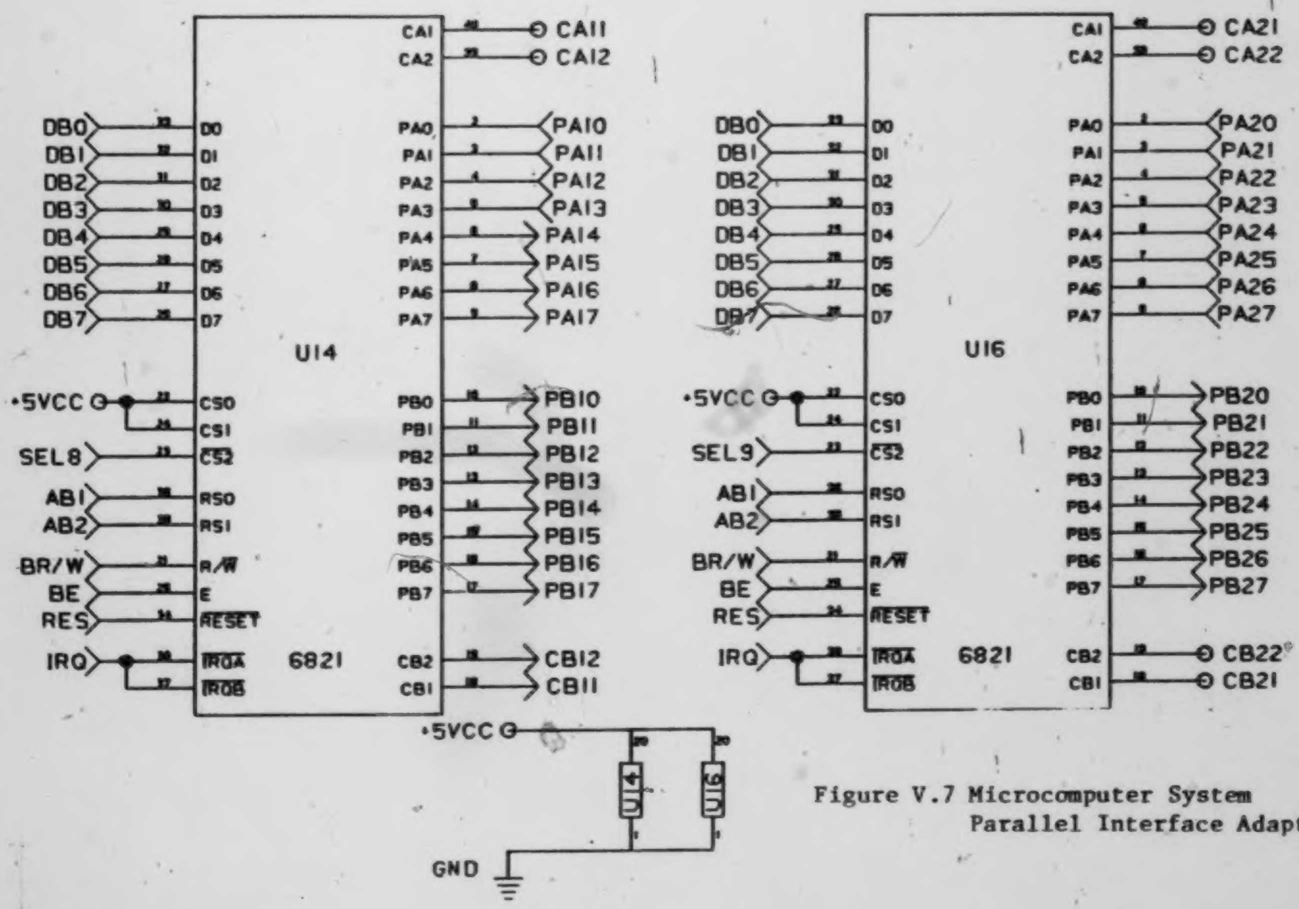

U14
6821
DB0
DB1
DB2
DB3
DB4
DB5
DB6
DB7
D0
D1
D2
D3
D4
D5
D6
D7
•5VCC
CS0
CS1
$\overline{\text{CS2}}$
SEL8
AB1
AB2
RS0
RS1
BR/W
BE
RES
R/$\overline{\text{W}}$
E
$\overline{\text{RESET}}$
IRQ
$\overline{\text{IRQA}}$
$\overline{\text{IRQB}}$
CA1
CA2
CA11
CA12
PA0
PA1
PA2
PA3
PA4
PA5
PA6
PA7
PA10
PA11
PA12
PA13
PA14
PA15
PA16
PA17
PB0
PB1
PB2
PB3
PB4
PB5
PB6
PB7
PB10
PB11
PB12
PB13
PB14
PB15
PB16
PB17
CB2
CB1
CB12
CB11
U16
6821
SEL9
CA21
CA22
PA20
PA21
PA22
PA23
PA24
PA25
PA26
PA27
PB20
PB21
PB22
PB23
PB24
PB25
PB26
PB27
CB22
CB21
•5VCC
GND
U14
U16
20
1

Figure V.7 Microcomputer System
Parallel Interface Adaptors

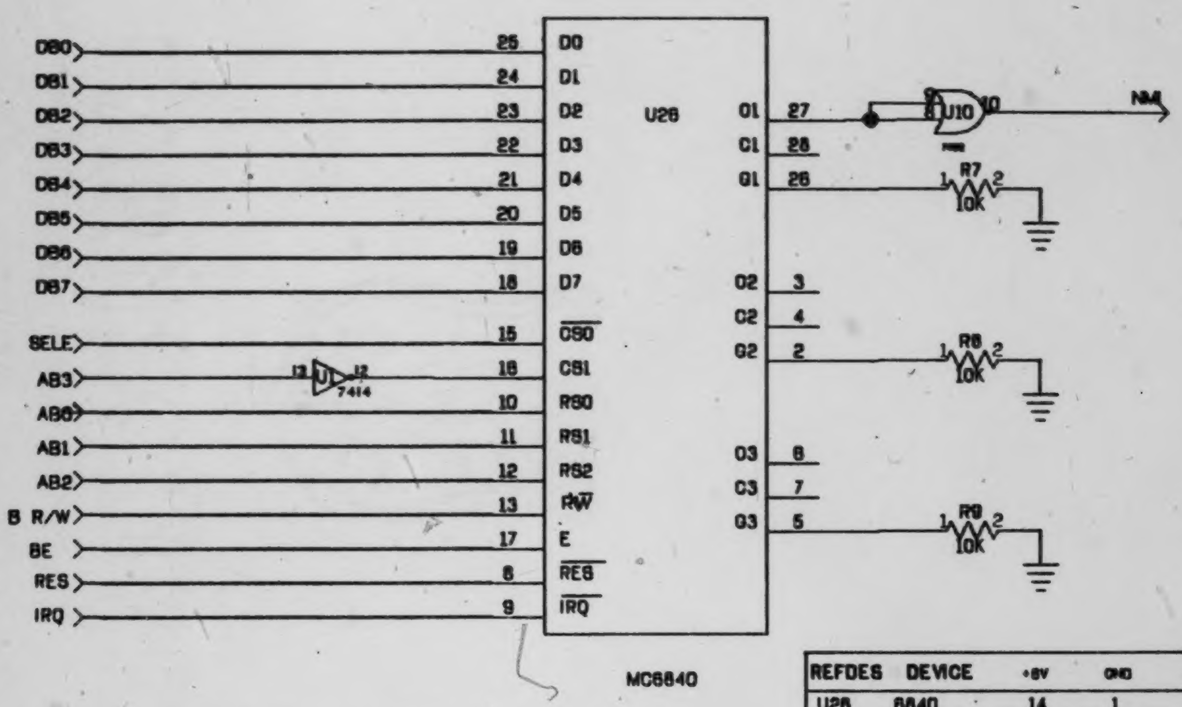

DB0
DB1
DB2
DB3
DB4
DB5
DB6
DB7
SELE
AB3
AB0
AB1
AB2
B R/W
BE
RES
IRQ
13
U1
12
7414
25
24
23
22
21
20
19
18
15
18
10
11
12
13
17
8
9
D0
D1
D2
D3
D4
D5
D6
D7
$\overline{\text{CS0}}$
CS1
RS0
RS1
RS2
R/$\overline{\text{W}}$
E
$\overline{\text{RES}}$
$\overline{\text{IRQ}}$
U26
MC6840
O1
C1
G1
O2
C2
G2
O3
C3
G3
27
28
26
3
4
2
6
7
5
9
8
U10
10
NMI
1
R7
2
10K
1
R8
2
10K
1
R9
2
10K

Figure V.8 Microcomputer System - Timer

REFDES	DEVICE	+5V	GND	-5V	-9V
U26	6840	14	1		
U10	7402	14	7		
	7414	14	7		

permanent magnet stepping motor is the HURST RAS3913-001 7.5° stepping motor used in this system [27].

The HURST permanent magnet stepping motor belongs to the class of stepping motors frequently identified as "can-stack" stepping motors with stepping angles typically in the range 7.5° to 20°. The motor contains two stacked sets of toothed stator poles and circular coils and a permanent magnet rotor with radial alternating North and South poles. The number of rotor poles is equal to the number of stator teeth in each set of poles. The stator pole sets are offset by 1/4 of a pole pitch. With both stator coils energised the rotor will align itself between the two equal stator fields.

A single step of the rotor is the result of a change of magnetic polarity of one set of stator teeth. This change in polarity is brought about by reversing the direction of current flow in the coil associated with those teeth. The rotor motion for the single step with no load applied is that of the damped oscillation as shown in Figure V.9. The damping characteristic of this curve may be modified by frictional and inertial loading and the sequence in which the windings are energised.

V.1.2.2 BIPOLAR AND BIFILAR OPERATION

The term bifilar and bipolar refer to two different types of coil windings that may be used in the stator coils. Bipolar windings contain a single coil in each stator half. The switching circuitry used to reverse the direction of current flow with this coil is typical of the full bridge or dual supply type.

Bifilar windings contain two windings in each stator half. When

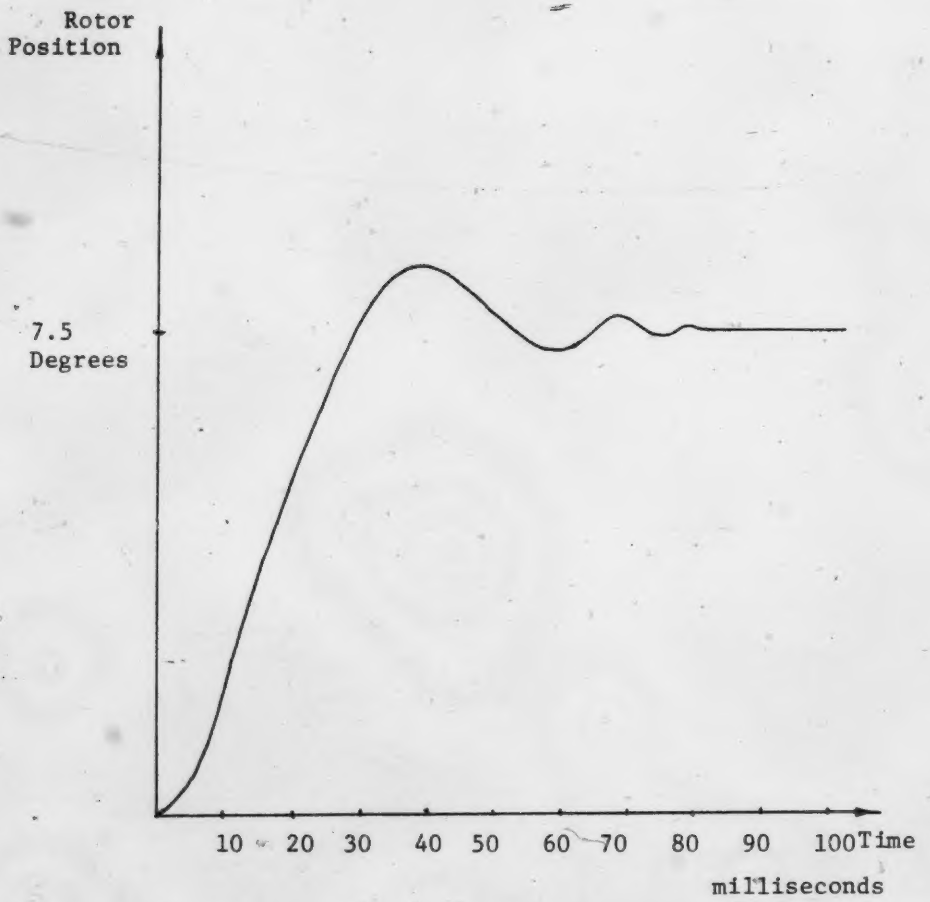


Figure V.9 Rotor Response for a Single Step With No Load
(Single Step Response)

they are connected as shown in Figure V.10 the magnetic field may be reversed by switching from one winding to the other.

The bifilar-wound stepper motors are widely used because of drive circuit simplicity. Since the winding volume per phases of the bifilar-wound stepper motor is only half that of the bipolar-wound stepper motor, the attainable ampere-turns for a given input power will necessarily be lower for the bifilar wound motor. The torque is therefore lower. However it is only lower in a holding mode or at low stepping rates. The reason is that the bipolar coil with its larger volume will ~~also~~ have a larger time constant (L/R) and at higher stepping rates the bipolar-wound motor's torque will decrease to approximately the same level as that of the bifilar-wound motor.

V.1.2.3 STEPPING SEQUENCE

The logic sequence required to rotate a bifilar wound permanent-magnet stepper motor is shown in Figure V.11. In this figure ϕ_1, ϕ_2, ϕ_3 and ϕ_4 represent the four phases of the bifilar wound stepper motor. It can be seen that the stepper motor can be rotated in the clockwise direction by energizing two of the four phases at a time in a particular sequence. Reversing the sequence will cause the stepper motor to rotate in the counterclockwise direction.

V.1.2.4 MICROPROCESSOR CONTROL OF PERMANENT MAGNET STEPPING MOTOR

The three HURST RAS3913-001 7.5°, 12V permanent magnet stepping motor control circuitry consists of the Parallel Interface Adaptors (PIA1 and PIA2) and the transistor drivers as shown in Figure V.12. Stepper motors "X" and "Y" are controlled by the eight output lines on the Port B side of the Parallel Interface Adaptor 1 (PIA1) and stepper

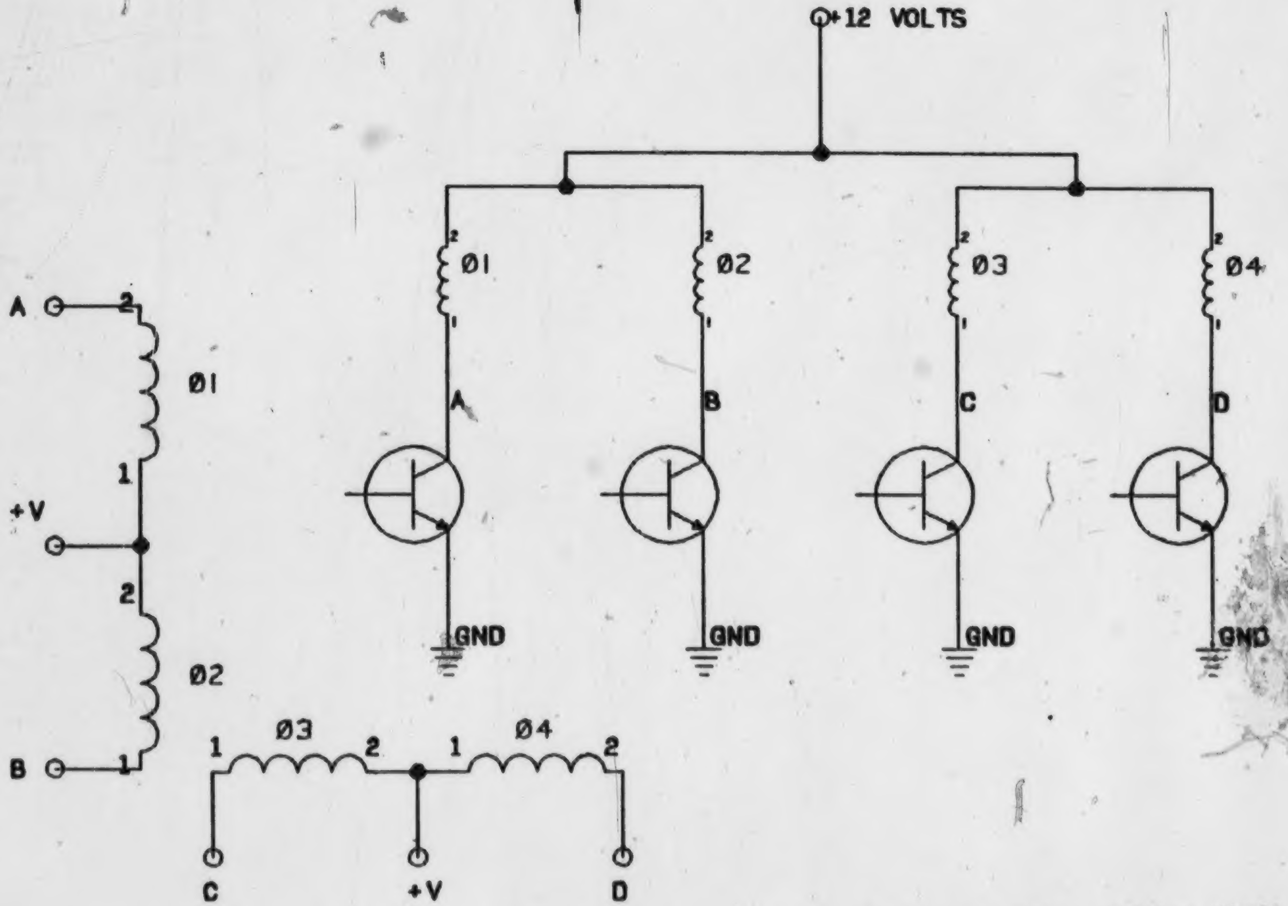
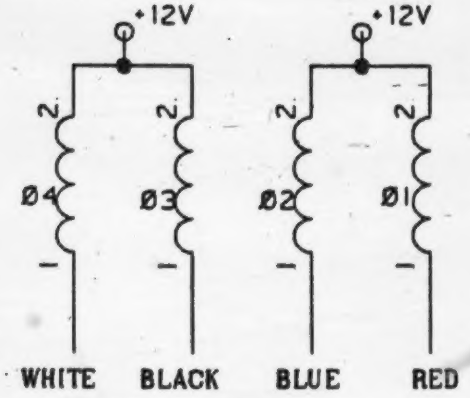

+12 VOLTS
2
01
1
A
GND
2
02
1
B
GND
2
03
1
C
GND
2
04
1
D
GND
A
2
01
1
+V
2
02
1
B
1
03
2
1
04
2
C
+V
D

Figure V.10 Permanent Magnet Stepper Motor Bifilar Winding


+12V
+12V
2
2
2
2
Ø4
Ø3
Ø2
Ø1
WHITE
BLACK
BLUE
RED

	Ø4 WHITE	Ø3 BLACK	Ø2 BLUE	Ø1 RED	
↑ CCW ROTATION	1	0	1	0	CW ROTATION ↓
	1	0	0	1	
	0	1	0	1	
	0	1	1	0	

Figure V.11 Six Lead Bifilar Winding Permanent Magnet Stepper Motor Stepping Sequence

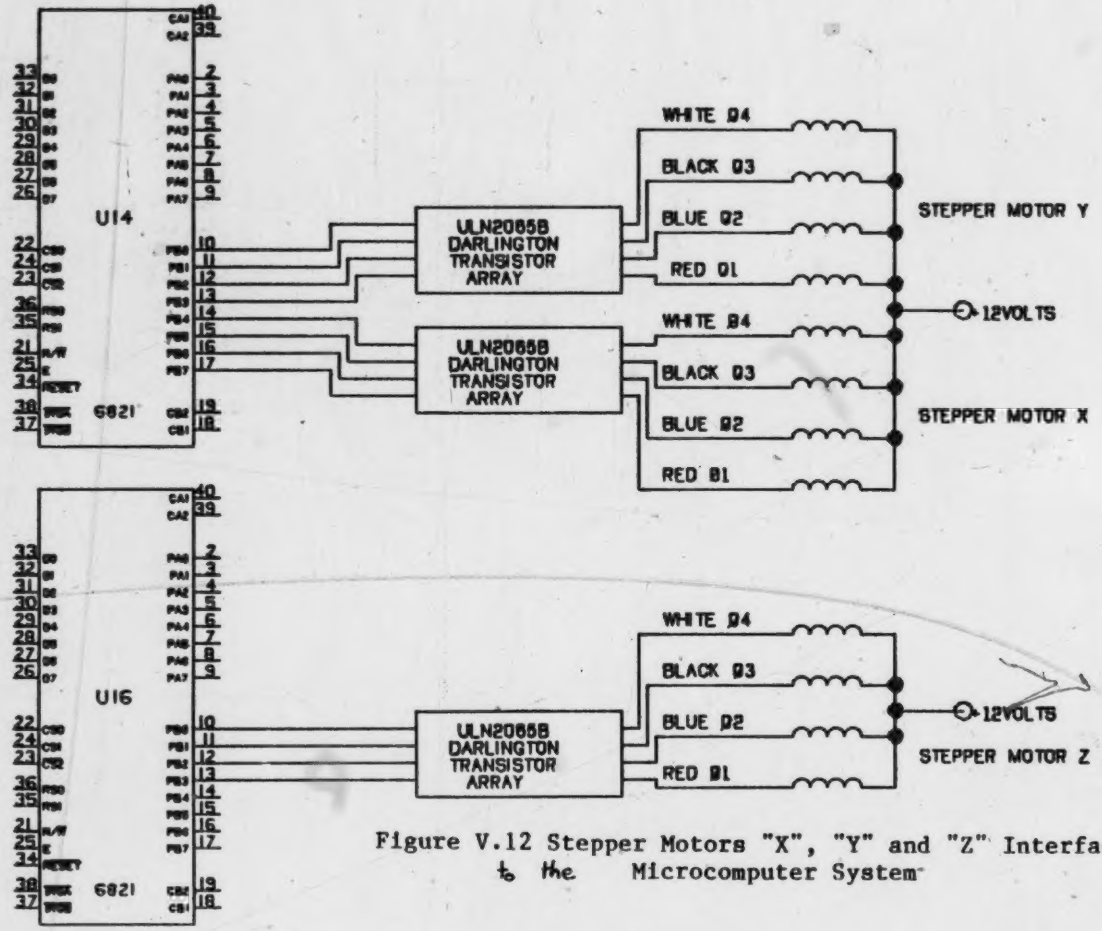

U14
U16
6821
ULN2065B DARLINGTON TRANSISTOR ARRAY
WHITE Ø4
BLACK Ø3
BLUE Ø2
RED Ø1
STEPPER MOTOR Y
STEPPER MOTOR X
STEPPER MOTOR Z
12VOLTS

Figure V.12 Stepper Motors "X", "Y" and "Z" Interface
to the Microcomputer System

motor "Z" is controlled by the four output lines on the Port B side of the Parallel Interface Adaptor 2 (PIA2). Since the drive capability of the Parallel Interface Adaptor output ports is in milliamperes only an additional interface stage is required to provide the necessary current drive. ULN2065B High Voltage High Current Darlington Array of Transistors was chosen to provide the interface between the digital circuitry and the 12V stepper motors. The ULN2065B has four similar circuits on a 16 PIN D.I.L. package as shown in Figure V.13. To control the switching of these Darlington transistors four peripheral data lines of the Parallel Interface Adaptor MC6821 (PIA) are used. When the peripheral data line of the PIA is high the ULN2065B Darlington transistor is switched "ON" causing current to flow through the particular winding.

V.1.3 ANALOG PROCESSING MODULE

The analog processing module is used to acquire data for the control of the three-dimensional manipulator. The joystick input is used for continuous control of the manipulator position in the "X", "Y" and "Z" directions. The analog interface module consists of:

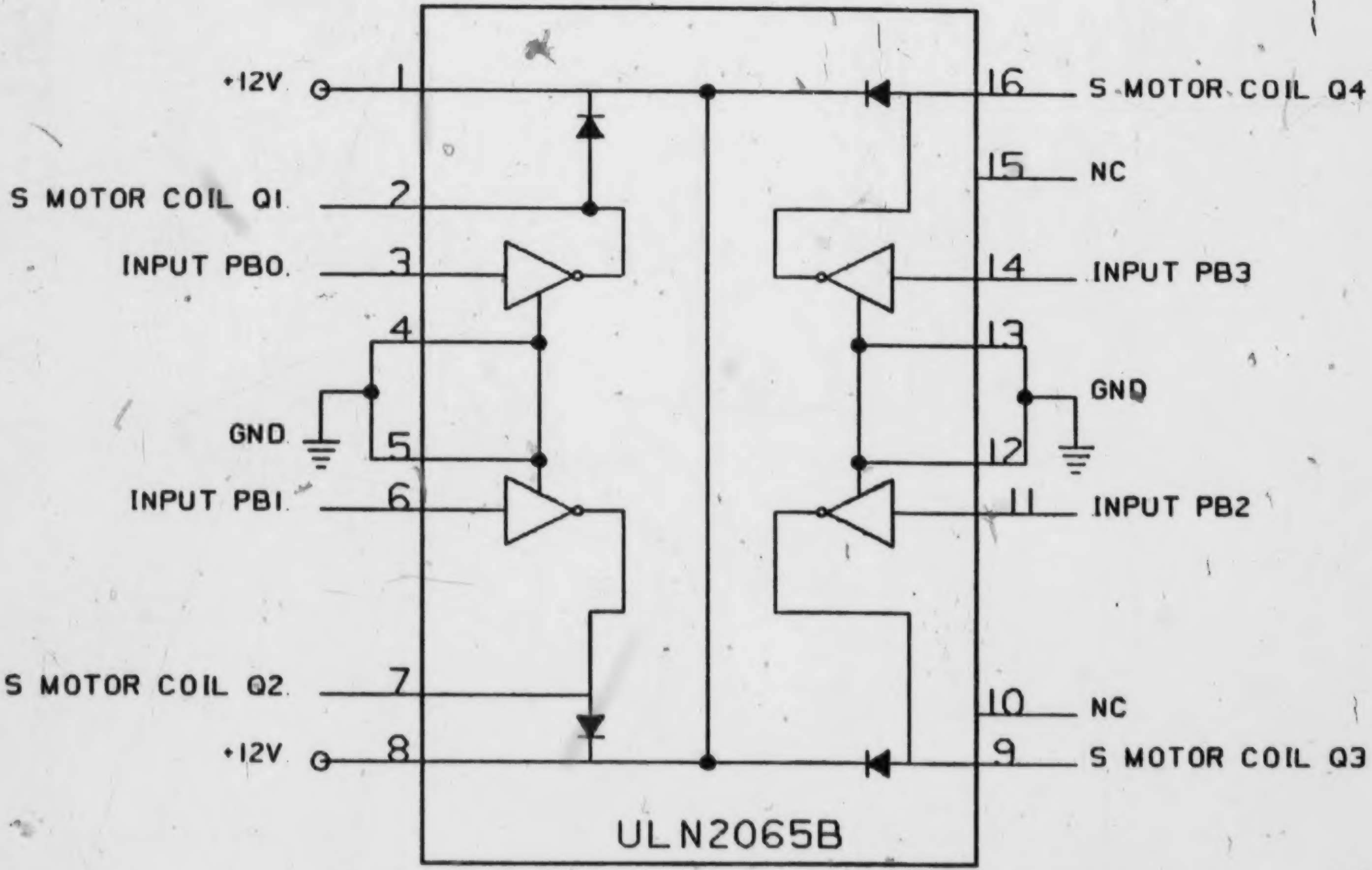
(i) Analog to digital converter AD7574.

(ii) Eight-to-one analog multiplexer and multiplexer control circuitry.

(iii) Hold circuit.

(iv) Joystick arrangement to give control in the three directions.

(v) Probe Amplifier.



+12V
1
S MOTOR COIL Q1
2
INPUT PB0
3
4
GND
5
INPUT PB1
6
S MOTOR COIL Q2
7
+12V
8
16
S MOTOR COIL Q4
15
NC
14
INPUT PB3
13
GND
12
11
INPUT PB2
10
NC
9
S MOTOR COIL Q3
ULN2065B

Figure V.13 ULN2065B High Voltage High Current Darlington Array

V.1.3.1 ANALOG-TO-DIGITAL CONVERTER

Analog-to-digital converters employ a variety of different circuit techniques to implement the conversion function. Of the various techniques available the choice depends on the resolution and speed required.

The AD7574 low cost 8-bit microprocessor compatible Analog-to-Digital Converter used in this system uses the successive approximations technique to provide an 8 bit parallel digital output. The control logic was designed to provide easy interface to most microprocessors. Figure V.14 shows the AD7574 analog-to-digital converter functional diagram [5]. Upon receipt of the start command via $\overline{C_S}$ or $\overline{R_D}$ pins, $\overline{BUSY}$ goes low indicating conversion is in progress. Successive bits starting with the most significant bit (MSB) are applied to the input of the digital-to-analog converter DAC. The comparator determines whether the addition of each successive bit causes the digital-to-analog converter output to be greater than or less than the analog input A_{IN}. If the sum of the digital-to- analog bits is less than A_{IN}, the trial bit is left ON and the next smaller bit is tried. If the sum is greater than A_{IN}, the trial bit is turned OFF and the next smaller bit is tried. Each successively smaller bit is tried and compared to A_{IN} in this manner until the lowest significant bit (LSB) decision has been made. At this time $\overline{BUSY}$ goes high indicating the successive approximation register contains a valid representation of the analog input. The $\overline{R_D}$ control can then be exercised to activate the three state buffers placing data on D_{B0} -D_{B7} data output lines.

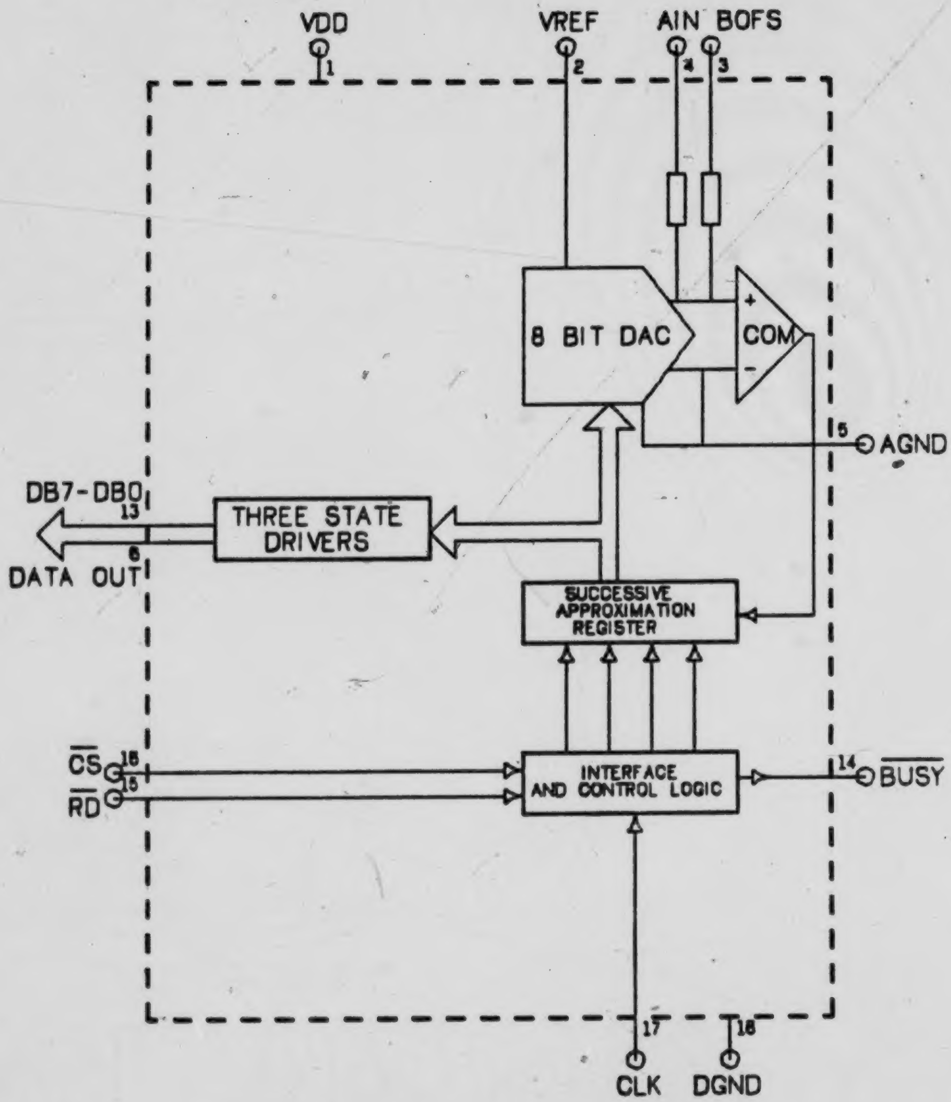

VDD
VREF
AIN
BOFS
1
2
4
3
8 BIT DAC
+
COM
−
5
AGND
DB7-DB0
13
6
DATA OUT
THREE STATE DRIVERS
SUCCESSIVE APPROXIMATION REGISTER
$\overline{CS}$
16
15
$\overline{RD}$
INTERFACE AND CONTROL LOGIC
14
$\overline{BUSY}$
17
18
CLK
DGND

Figure V.14 AD7574 Analog-to-Digital Converter Functional Diagram

V.1.3.2 EIGHT-TO-ONE ANALOG MULTIPLEXER

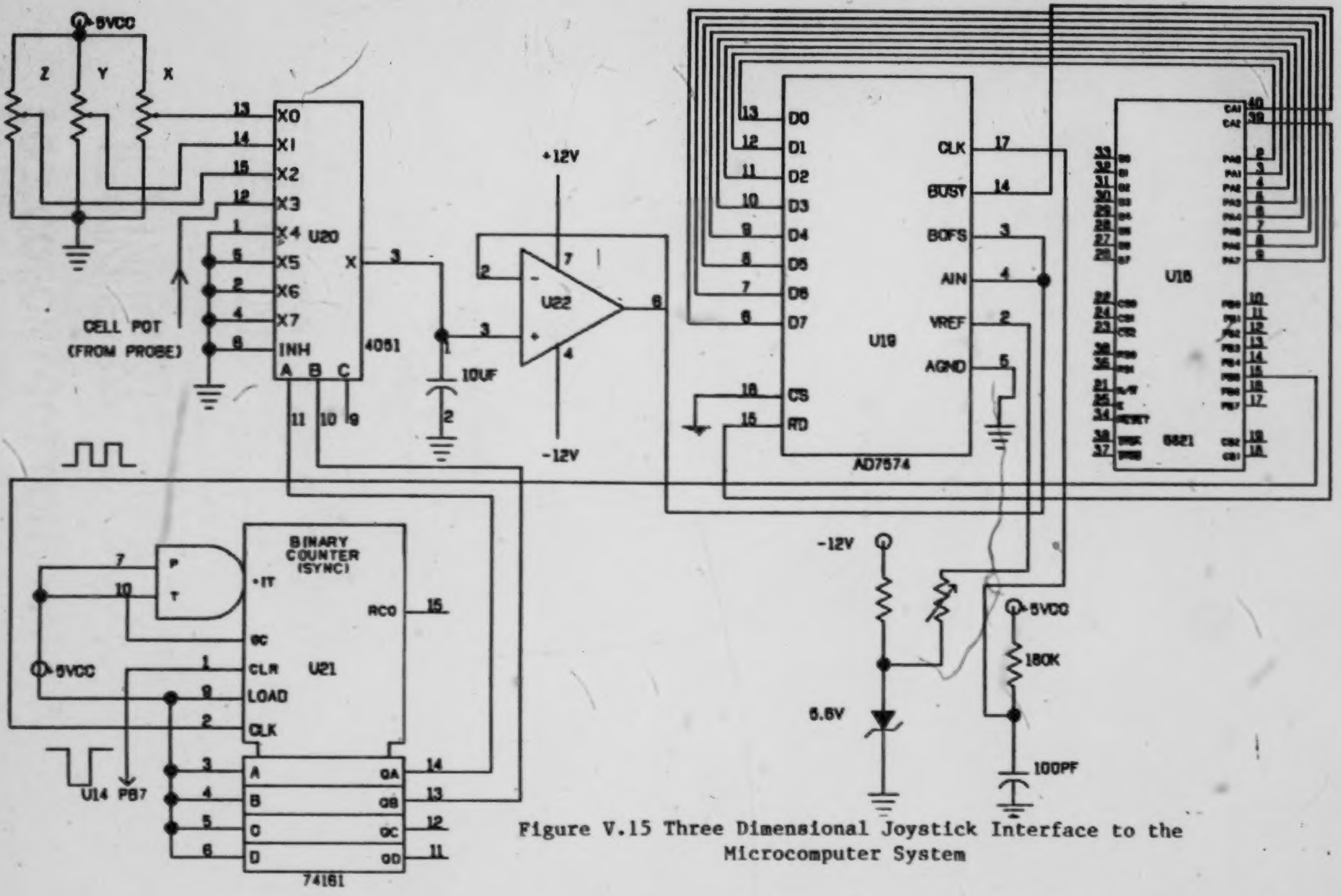
Analog multiplexers are the circuits that time share an analog-to-digital converter among a number of different analog channels. Since the analog-to-digital converter is the most expensive element in the data acquisition system, multiplexing analog inputs to the analog-to-digital converter (ADC) is an economical approach. Usually the analog multiplexer operates into the sample-and-hold circuit which holds the required analog voltage long enough for the analog-to-digital converter (ADC) to complete conversion.

The analog multiplexer used in this system is a eight-to-one MC14051B multiplexer. This multiplexer consists of an array of parallel electronic switches connected to a common output line. Only one switch is turned on at a time. The multiplexer also contains a decoder circuit which decodes a binary input word and turns on an appropriate switch.

The timing of the analog channel switching is controlled by the programme sequencer. The programme sequencer is controlled by the microcomputer module via Parallel Interface Adaptor 2 (PIA2) data line PB5.

V.1.3.3 JOYSTICK INTERFACE TO THE MICROCOMPUTER SYSTEM

The detailed circuit arrangement of the three dimensional joystick interface to the microcomputer system is shown in Figure V.15. The complete circuit is wire-wrapped on the same board as the microcomputer module with the exception of the microelectrode interface amplifier which is wire-wrapped on the second board. The analog-to-digital converter (ADC) is the main element which interfaces the analog



5VCC
Z
Y
X
13
14
15
12
1
5
2
4
6
X0
X1
X2
X3
X4
X5
X6
X7
INH
A
B
C
U20
X
4051
11
10
9
CELL POT
(FROM PROBE)
3
1
10UF
2
+12V
7
2
3
U22
4
6
-12V
D0
D1
D2
D3
D4
D5
D6
D7
CS
RD
18
15
U19
AD7574
CLK
BUSY
BOFS
AIN
VREF
AGND
17
14
3
4
2
5
U18
6821
-12V
5.6V
5VCC
180K
100PF
BINARY
COUNTER
(SYNC)
P
T
7
10
•IT
GC
CLR
LOAD
CLK
RCO
15
U21
5VCC
1
9
2
3
4
5
6
A
B
C
D
QA
QB
QC
QD
14
13
12
11
74161
U14 PB7

Figure V.15 Three Dimensional Joystick Interface to the Microcomputer System

signals/circuits to the microcomputer system. The analog-to-digital converter (ADC) AD7574 is connected in the Read Only Memory (ROM) mode in this system. Figure V.16 and Figure V.17 show the truth table and the timing requirements for interfacing the analog-to-digital converter (ADC) like a Read Only Memory (ROM).

In this mode $\overline{C_S}$ is held low and the analog-to-digital converter (ADC) operation is controlled by $\overline{R_D}$ input. The $\overline{R_D}$ line is connected to the control line CA2 and the $\overline{\text{Busy}}$ line is connected to the control line CA1 of the Parallel Interface Adaptor 2 (PIA2). The control line CA2 is used in a level (manual) output mode to provide an active low start conversion pulse of sufficient length. The conversion is automatically restarted when $\overline{R_D}$ returns high.

The data is read when $\overline{R_D}$ is low. Attempting a data read before $\overline{\text{Busy}}$ is high will result in incorrect data being read.

The advantage of Read Only Memory (ROM) mode is its simplicity. The major disadvantage is that the data obtained is relatively poorly defined in time in as much as executing a data read automatically starts a new conversion. The problem is overcome by executing two Reads separated by a delay and using only the data obtained from the second read.

The analog section of the analog-to-digital converter (ADC) is connected in an unipolar operating mode. The Binary Offset (B_{OFS}) and Analog In (A_{IN}) pins are connected together. The V_{ref} is connected to -5V reference. This mode enables positive input signals of up to 5V to be applied and produce an unsigned binary output.

Each channel is selected by applying a pulse to clock the counter

AD7574				OPERATIONS
INPUTS			OUTPUTS	
$\overline{CS}$	$\overline{RD}$	$\overline{BUSY}$	DB7-DB0	
L	↓	H	HIGH Z → DATA	DATA READ
L	↑	↓	DATA → HIGH Z	RESET AND START NEW CONVERSION
L	↓	L	HIGH Z	NO EFFECT CONVERTER BUSY
L	↑	L	HIGH Z	NOT ALLOWED. CAUSES INCORRECT CONVERSION

Figure V.16 AD7574 ADC ROM Mode Truth Table

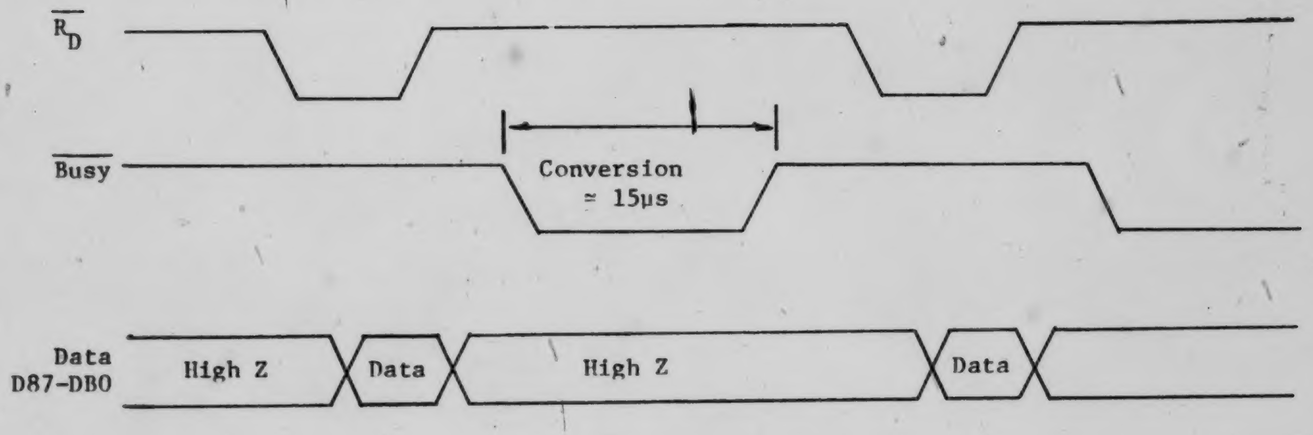

$\overline{R_D}$
$\overline{\text{Busy}}$
Conversion ≃ 15μs
Data D87-DB0
High Z
Data
High Z
Data

Figure V.17 AD7574 ADC ROM Mode Timing Diagram

via the Parallel Interface Adaptor 2 (PIA2) data line PB5. The outputs of the counter are connected to the control inputs of the analog multiplexer. The selected channel signal is digitised by the analog-to-digital converter and stored in memory locations NUMBXB (x Buffer), NUMBYB (Y Buffer), NUMBZB, (Z Buffer) and NUMBVT (VTH Buffer).

V.1.3.4 THREE DIMENSIONAL JOYSTICK DESIGN

The three dimensional joystick was designed to enable the control of microelectrodes in the X-Y-Z plane. Two, wire wound, 5 kilo-ohms potentiometer were mounted at 90^{o} to each other to give control in the X-Y plane. To control the microelectrode over ± 64 microns it was necessary to control the potentiometer over the full resistance range. This was achieved by coupling the X-Y potentiometers to the joystick with a mechanical linkage having a 1:4 gear ratio. With the joystick-top opening set to give maximum joystick movement of 75^{o}, it was possible to control the X-Y potentiometer over the full 300^{o} range thus giving 256 digitised levels for the control of the stepper motors.

The potentiometer used for the control of the "Z" stepper motor is a ten turn, wire-wound, 5 kilo-ohm potentiometer. This multi-turn "Z" potentiometer enables a very accurate control of the "Z" stepper motor. Wire wound potentiometers are used for better accuracy.

Another feature of this three-dimensional joystick is the non-self centering nature of the joystick. This feature prevents the "X" and "Y" motors returning to its initial position after each setting of the joystick. The pressure plate provides not only the non-self centering feature but also acts as top cover, thus preventing dust from getting inside thus clogging the movement of the mechanical parts.

In the actual experimental situation the microelectrode is positioned in the X-Y plane first and then any movement of the microelectrode in the "Z" direction takes place. The X-Y potentiometers were coupled to the joystick and the multi-turn "Z" potentiometer was mounted on the side wall of the joystick arrangement. The three potentiometers were wired in parallel across the regulated 5 volts supply with their variable terminals as inputs to the analog multiplexer. The three-dimensional joystick was electrically connected to the microcomputer system via a RCA plug and socket arrangement.

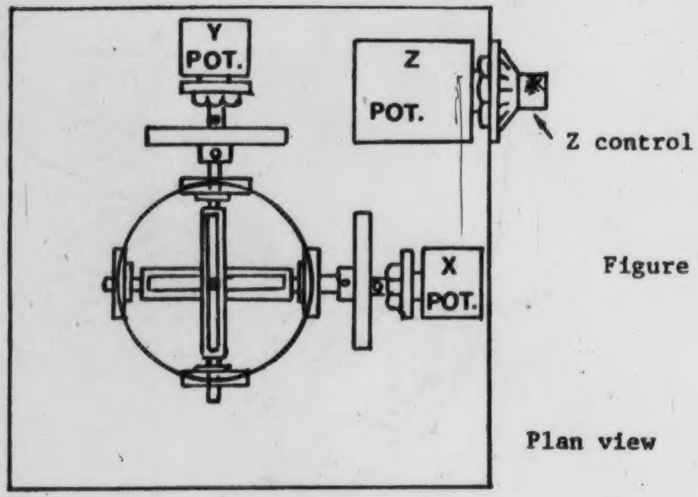
A detailed three-dimensional joystick drawing is shown in Figure V.18.

V.1.3.5 PROBE AMPLIFIER

An interesting characteristic of a cell is that it has a voltage gradient across the cell wall. The difference between the inside and the outside of the cell wall is in millivolts, the exact value depends on the cell type. The minimum potential is approximately -100 millivolts. A UA741 operational amplifier in inverting mode with a gain of 19.5 is used. The potential scaled to 0-5 volts is fed into one channel of the MC14051B multiplexer. The detailed circuit arrangement is shown in Figure V.19.

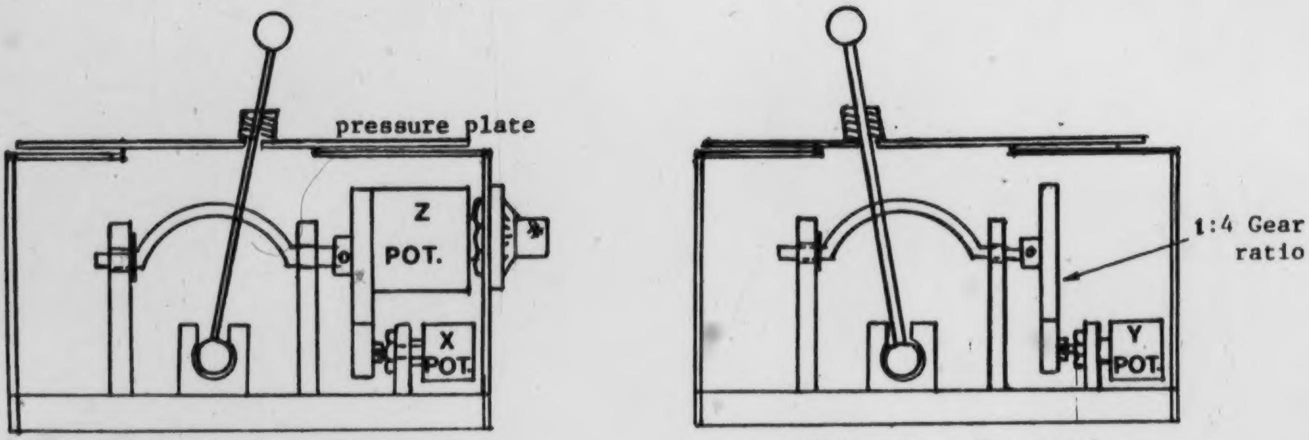
V.1.4 KEYBOARD INPUT AND DISPLAY SYSTEM

The keyboard software is under Interrupt control and is used to enter values of displacement of the manipulator in the "X", "Y" and "Z" directions, alter values of maximum threshold voltages, enable the


Y
POT.
Z
POT.
Z control
X
POT.

Plan view

Figure V.18 Three Dimensional Joystick


pressure plate
Z
POT.
X
POT.
1:4 Gear
ratio
Y
POT.

Front view – X control

Side view – Y control

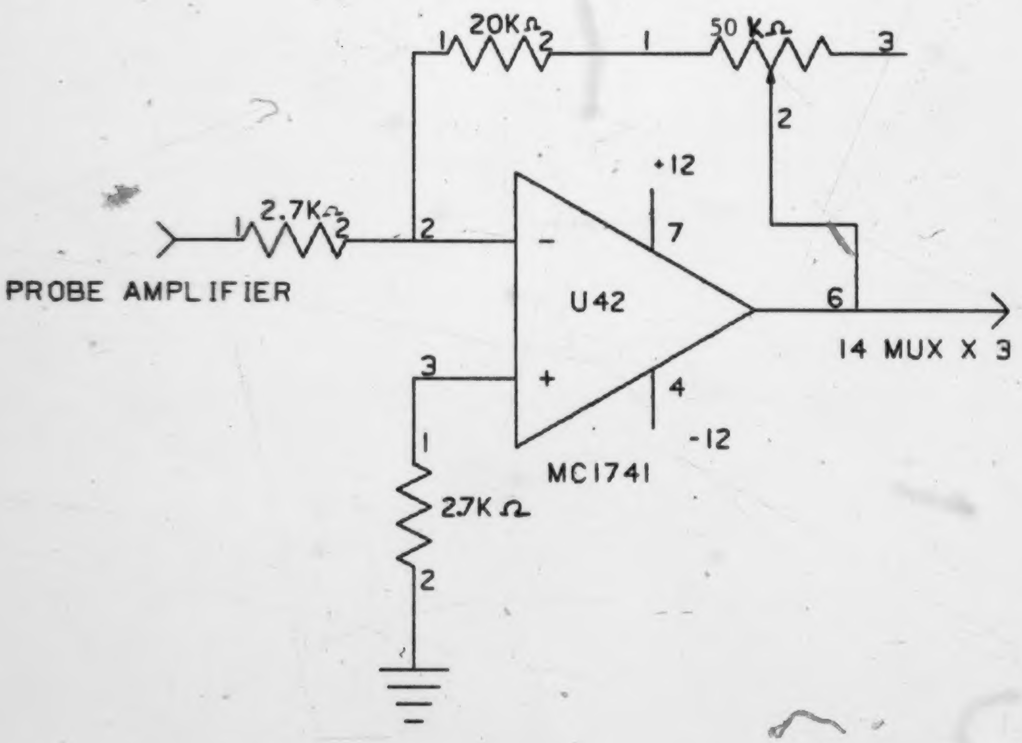

20KΩ
1
2
1
50 KΩ
3
2
+12
2.7KΩ
1
2
2
−
7
PROBE AMPLIFIER
U42
6
14 MUX X 3
3
+
4
1
-12
MC1741
2.7K Ω
2

Figure V.19 Probe Voltage Amplifier

manipulator to return to "home" position.

The keyboard interface consists of:

(i) An MM74C922 16 key encoder.
(ii) A 4x4 matrix keyboard.

V.1.4.1 THE MM74C922 16 KEY ENCODER

This CMOS key encoder provides all necessary logic to fully encode an array of SPST switches. The keyboard scan can be implemented by an external clock or external capacitor. This encoder also has on-chip pull up devices which permit up to 50K "ON" resistance to be used. The internal de-bounce circuit needs only a single external capacitor. The "data available" output line goes to a high level when a valid keyboard entry has been made. The data available returns to a low level when the entered key is released, even if another key is depressed. The data available will return to high level to indicate acceptance of the new key after the normal de-bounce period; this two key roll-over is provided between any two keys. The internal register remembers the last key pressed even after the key is released. Figure V.20 and Figure V.21 show the block diagram of the MC74C922 16 key encoder and timing waveforms [52].

V.1.4.2 KEYBOARD INTERFACE

The detailed circuit diagram of the keyboard interface is shown in Figure V.22. The MM74C922 key encoder interface is wire-wrapped on the interface board with 1μF and 0.1μF external capacitors connected between ground and KBN and OSC pins respectively. This arrangement enables the keyboard entry to operate in asynchronous data entry mode. The MM74C922 key encoder is interfaced to the microcomputer system via

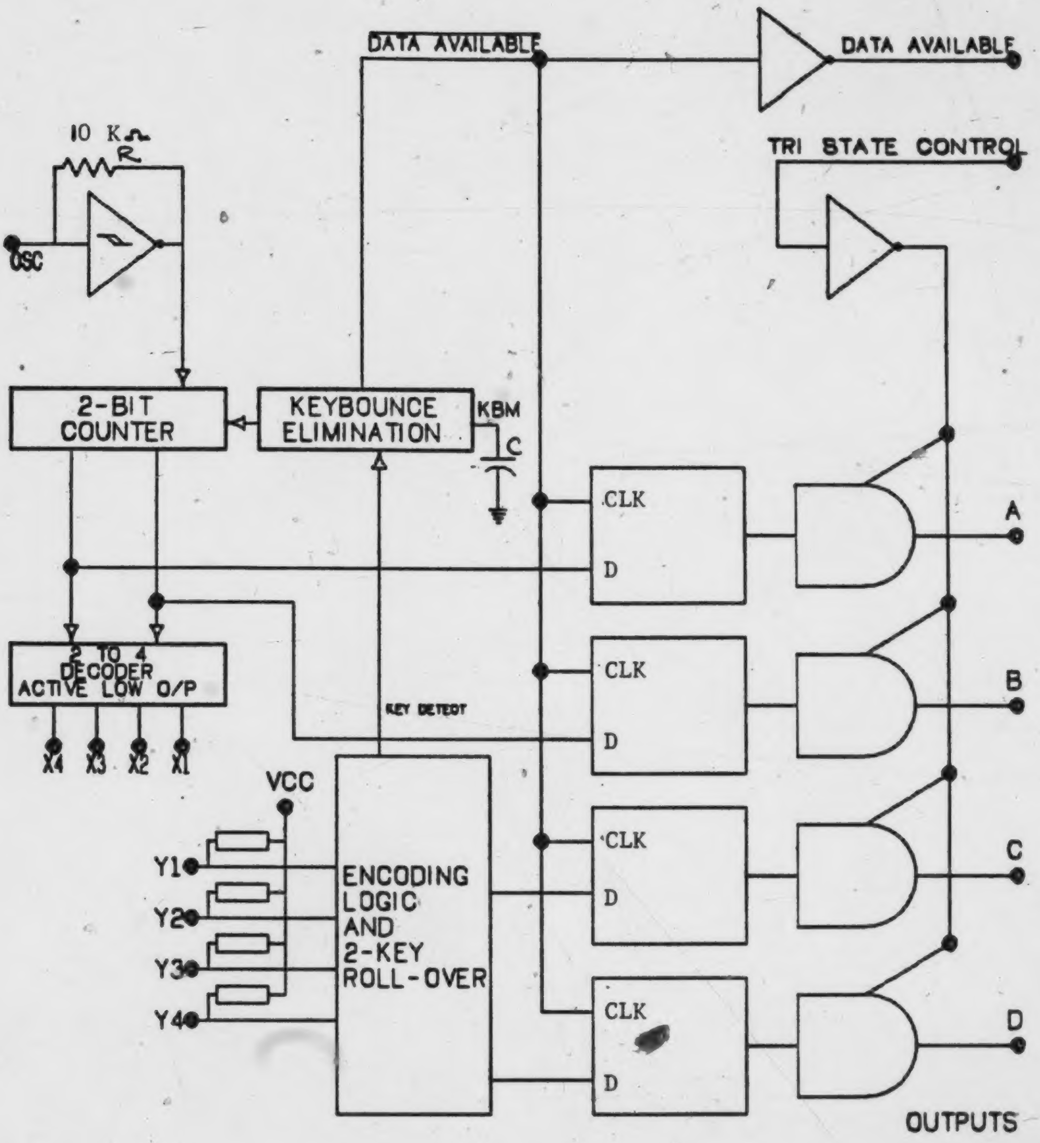
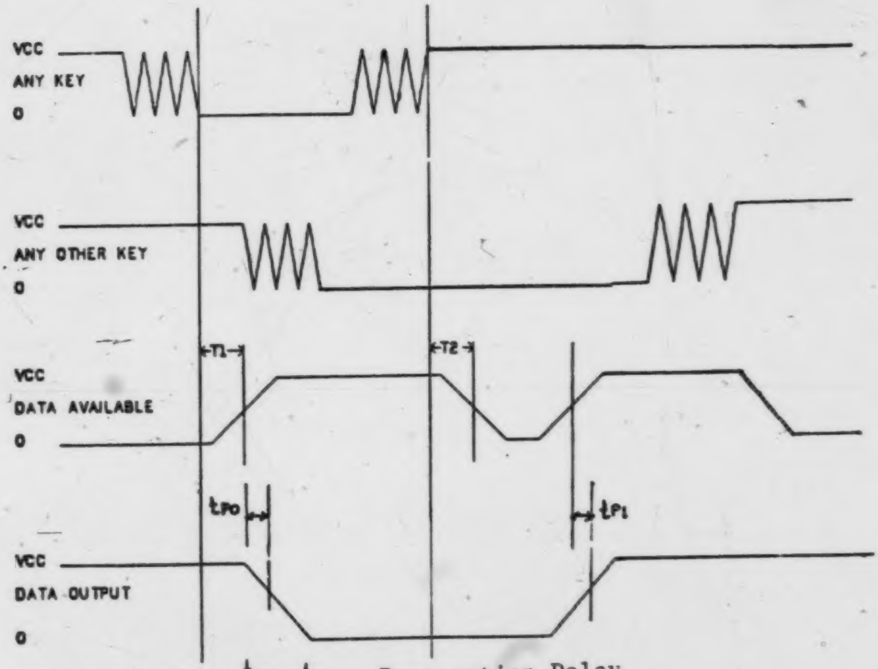

DATA AVAILABLE
DATA AVAILABLE
TRI STATE CONTROL
10 KΩ
R
OSC
2-BIT COUNTER
KEYBOUNCE ELIMINATION
KBM
C
CLK
D
A
B
C
D
2 TO 4 DECODER ACTIVE LOW O/P
X4
X3
X2
X1
KEY DETECT
VCC
Y1
Y2
Y3
Y4
ENCODING LOGIC AND 2-KEY ROLL-OVER
OUTPUTS

Figure V.20. MM74C922 16 Key encoder block diagram


VCC
ANY KEY
0
VCC
ANY OTHER KEY
0
T1
T2
VCC
DATA AVAILABLE
0
tPO
tP1
VCC
DATA OUTPUT
0

t_{p0}, t_{p1} = Propagation Delay

T1 = T2 = RC

Figure V.21 MM74C922 Switching Time Waveform

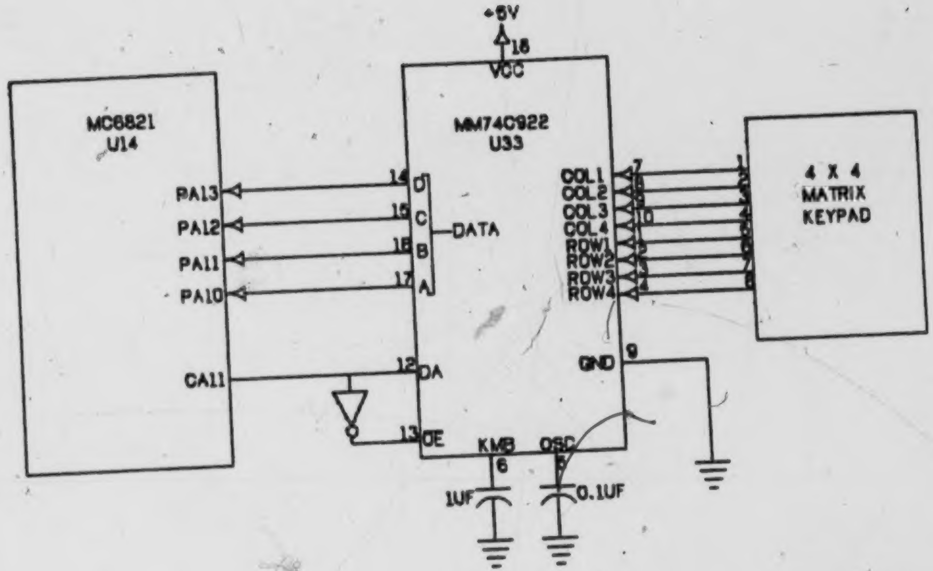

+5V
18
VCC
MC6821
U14
PA13
PA12
PA11
PA10
CA11
MM74C922
U33
14
D
15
C
16
B
17
A
DATA
12
DA
13
OE
KMB
6
OSC
5
1UF
0.1UF
COL1
COL2
COL3
COL4
ROW1
ROW2
ROW3
ROW4
7
10
4
GND
9
4 X 4
MATRIX
KEYPAD
1
2
3
4
5
6
7
8

Figure V.22 Keyboard Interface to the Microcomputer System

Parallel Interface Adaptor 1 (PIA1).

V.1.4.3 DISPLAY SYSTEM

The display system consists of

(i) An Intersil ICM7218A series CMOS Universal LED driver system.

(ii) 16 MAN6760C seven segment common anode displays.

V.1.4.3.1 THE INTERSIL ICM7218A SERIES CMOS UNIVERSAL LED DRIVER

The ICM7218A series CMOS Universal LED driver system provides, in a single package, all the circuitry necessary to interface the Motorola MC6809 microcomputer system to a LED display. Included on the chip is an 8x8 static memory array providing storage for the displayed information, two types of seven segment decoders, all the multiplex scan circuitry and the high power digit and segment drivers.

The ICM7218A is intended to be used primarily in a microprocessor system. Data is read directly from the I/O bus of the microcomputer system. Two control lines, $\overline{\text{WRITE}}$ and MODE define chip select, which results in the reading of either four bits of control information (data coming, $\overline{\text{shutdown}}$, decoder, Hexadecimal or Code B decoding) or eight bits of display input data. Display input data (8 words, 8 bits each) is automatically sequenced into the memory on successive negative going $\overline{\text{WRITE}}$ pulses. Data may be displayed either directly or decoded in Hexadecimal or Code B formats. Figure V.23 and Figure V.24 show the block diagram and control input definitions for the ICM7218A series CMOS Universal eight digit LED driver [28].

The ICM7218A series CMOS LED driver has three input data formats, namely:

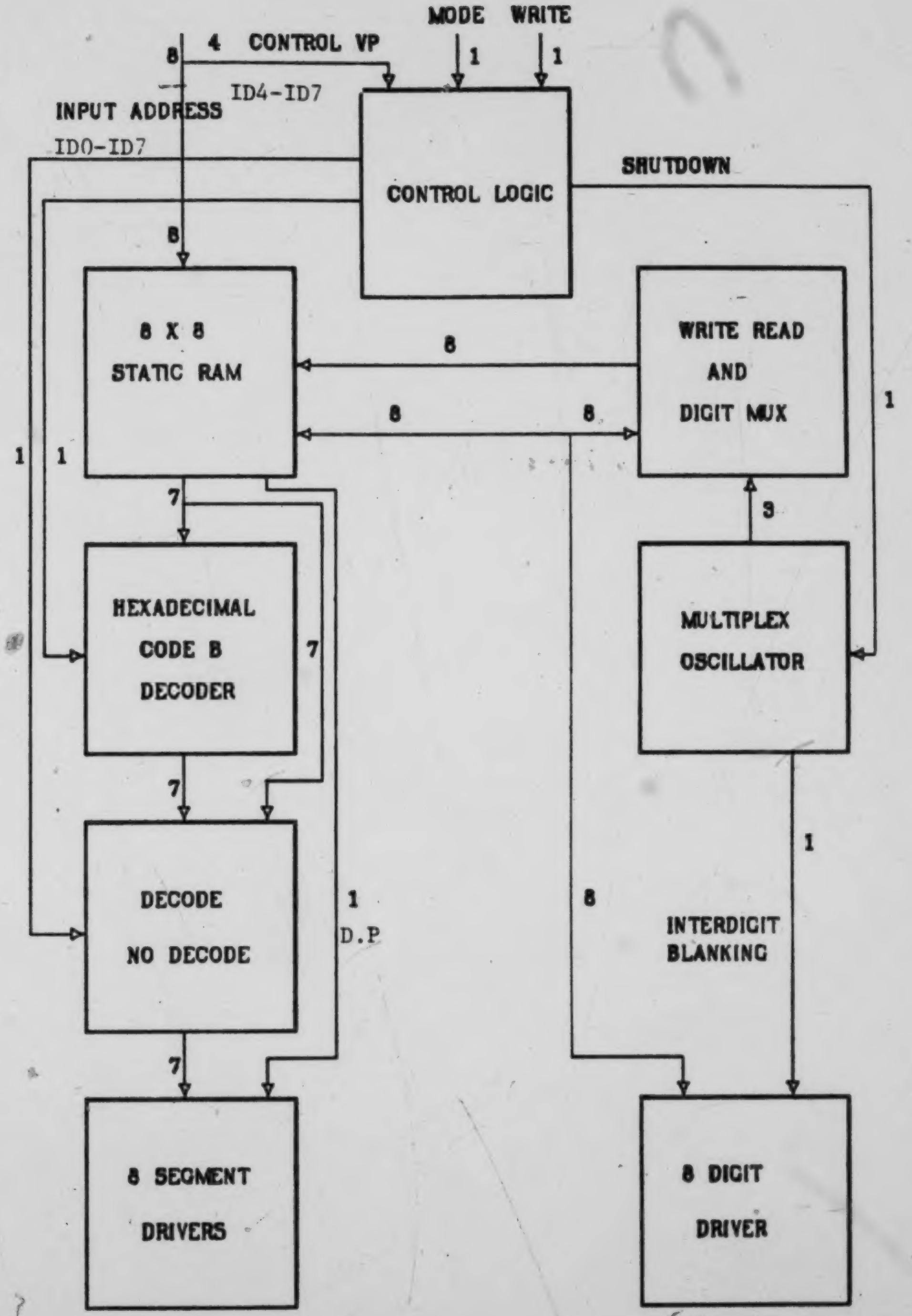

MODE
WRITE
1
1
8
4
CONTROL VP
ID4-ID7
INPUT ADDRESS
ID0-ID7
SHUTDOWN
CONTROL LOGIC
8
8 X 8
STATIC RAM
8
WRITE READ
AND
DIGIT MUX
8
8
1
1
1
7
3
HEXADECIMAL
CODE B
DECODER
7
MULTIPLEX
OSCILLATOR
7
1
DECODE
NO DECODE
1
D.P
8
INTERDIGIT
BLANKING
7
8 SEGMENT
DRIVERS
8 DIGIT
DRIVER

Figure V.23. ICM7218A LED driver block diagram

Input	Terminal	Voltage	Function
Write	8	High	Input not loaded into memory
		Low	Input loaded into memory
Mode	9	High	Load control word on write pulse
		Low	Load input data on write pulse
ID6	5	High	Hexadecimal decoding
		Low	Code B
ID5	6	High	No decode
		Low	Decode
ID7	7	High	Data coming
		Low	No data coming
ID4	10	High	Normal operation
		Low	Shutdown mode
Input Data ID0-ID7	11,12,13 14,5,6,10 7	High	Load's "1"
		Low	Load's "0"

Figure V.24 ICM7218A Control Input Definition

(i) No-decode - the inputs directly control the outputs.
(ii) Hexadecimal decoding.
(iii) Code B decoding.

V.1.4.3.2 DISPLAY INTERFACE

The sixteen, seven segment common-anode displays are interfaced to the microcomputer system via two ICM7218A driver systems and the Parallel Interface Adaptor 2 (PIA2) as shown in Figure V.25. The control instructions are read from the input bus lines if MODE is high and $\overline{\text{WRITE}}$ is low. The instructions occur on four lines and are decode/no-decode type of decode (if desired), shutdown/no shutdown and data coming/not coming. After the control instruction has been read (with the data coming instruction) display data can be written into memory with each following negative going transition of $\overline{\text{write}}$, mode being low. Eight memory address locations in the 8x8 static memory are automatically sequenced on each successive $\overline{\text{WRITE}}$ pulse. After eight $\overline{\text{WRITE}}$ pulses have occurred, further pulses are ignored and the display interface returns to normal display operation until a new control word is transferred. It is not possible to change for example digit #7 only without refreshing the data for all the other digits. Figure V.26 shows the ICM7218A chip address sequence.

V.1.5 THE OUTPUT MODULE

The output module consists of:

(i) The Stepper Motor Interface to the hydraulic system.
(ii) The Hydraulic system.
(iii) The three-dimensional hydraulic controlled manipulator with electrode holder.

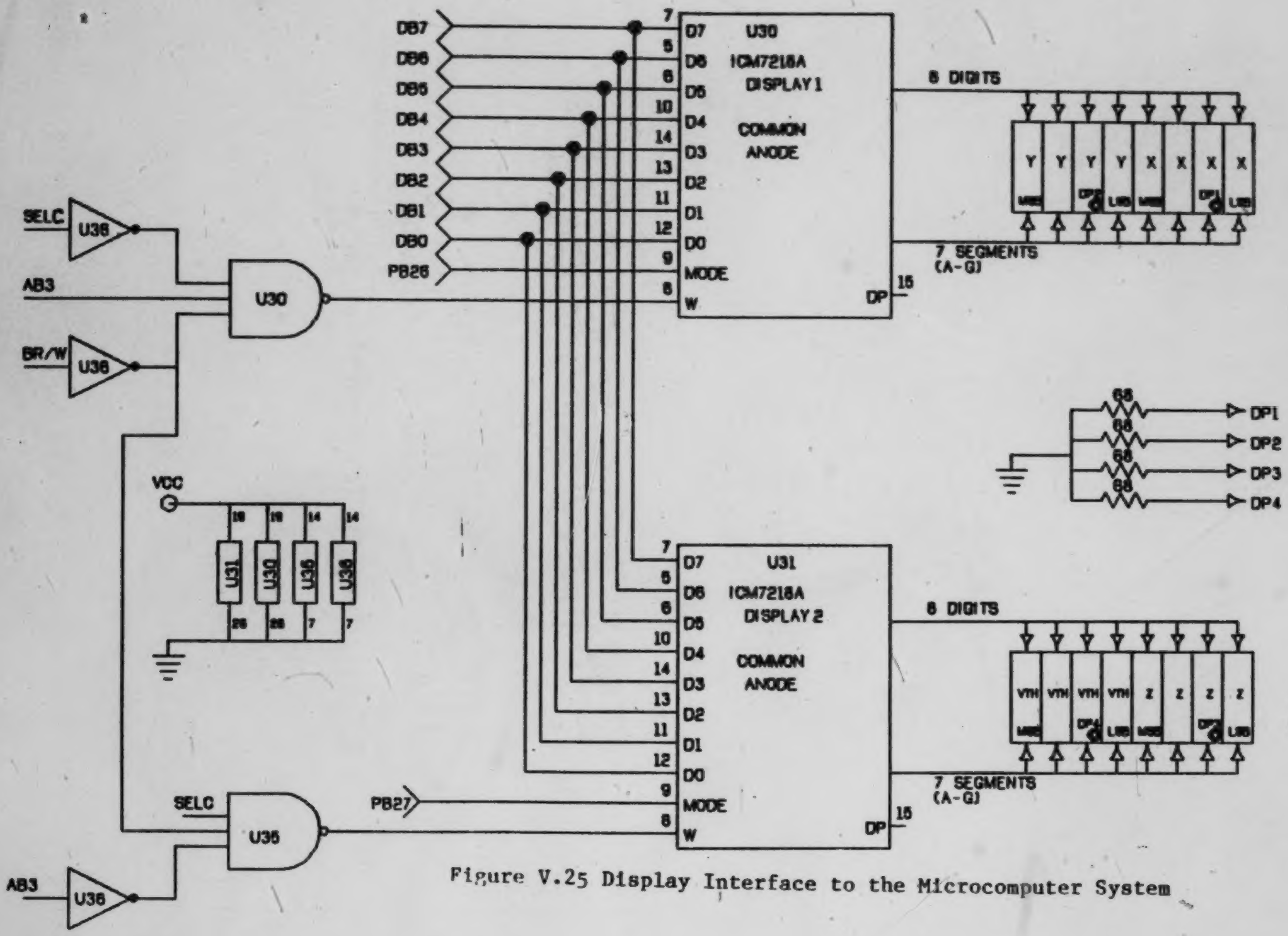

DB7
DB6
DB5
DB4
DB3
DB2
DB1
DB0
PB26
PB27
SELC
AB3
BR/W
U36
U30
VCC
U31
U30
U36
U36
D7
D6
D5
D4
D3
D2
D1
D0
MODE
W
DP
U30
ICM7218A
DISPLAY 1
COMMON
ANODE
U31
ICM7218A
DISPLAY 2
COMMON
ANODE
8 DIGITS
7 SEGMENTS
(A-G)
Y
X
VTH
Z
MSB
LSB
DP1
DP2
DP3
DP4
68

Figure V.25 Display Interface to the Microcomputer System

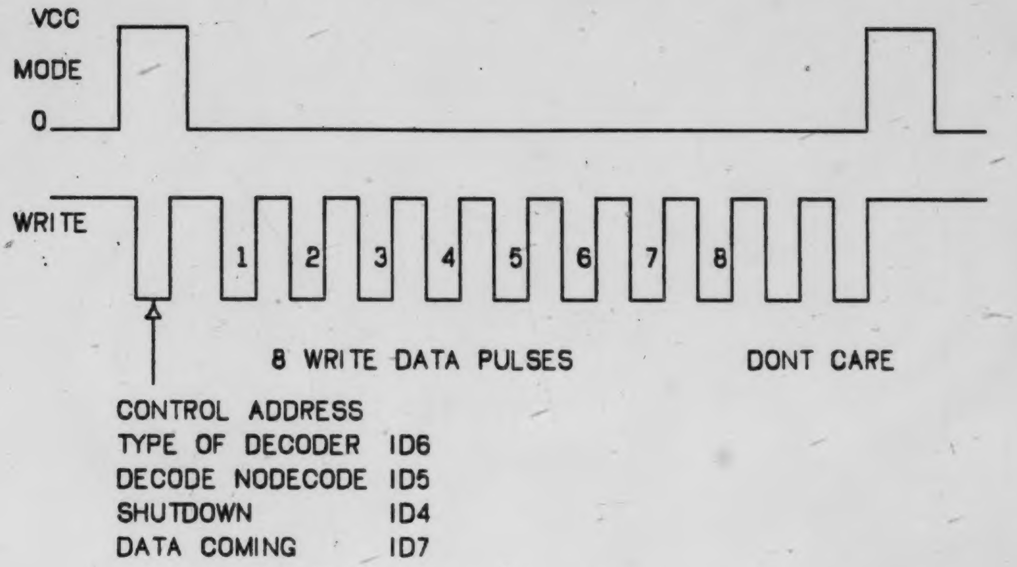

VCC
MODE
0
WRITE
1
2
3
4
5
6
7
8
8 WRITE DATA PULSES
DONT CARE
CONTROL ADDRESS
TYPE OF DECODER ID6
DECODE NODECODE ID5
SHUTDOWN ID4
DATA COMING ID7

Figure V.26 ICM7218A LED Driver Chip Address Sequence

V.1.5.1 THE STEPPER MOTOR INTERFACE TO HYDRAULIC SYSTEM

The three stepper motors "X", "Y" ad "Z" are linked to the hydraulic system via three high precision non-rotating spindle micrometers. This arrangement enables the circular motion of the stepper motors to be converted to the linear motion. The micrometers used in the system are 0.5mm linear displacement per revolution non-rotating spindle micrometers. This means that 48 steps of the stepper motor (the 7.5^{o} step angle gives $360/7.5^{o}$ steps/revolution) will give 0.5mm linear displacement of the micrometer.

The maximum number of steps that the stepper motor can take is determined by the analog-to-digital converter used in the system. Since the system uses AD7574 8-bit converter the maximum number of levels available is 256. Thus for both positive and negative rotation the maximum number of step = ± 128.

Thus maximum linear motion of the micrometer

$$= \pm \frac{128}{48} \times 0.5\text{mm}$$

$$= \pm 1.33 \text{ mm.}$$

The mechanical details of the stepper motor interface to the hydraulic system is shown in Figure V.27.

V.1.5.2 THE HYDRAULIC SYSTEM

The hydraulic system was chosen to interface stepper motors/micrometers arrangements and the three dimensional manipulator:

(i) to provide sub-micron displacement of the microelectrode in the "X", "Y" and "Z" directions for every step taken by the

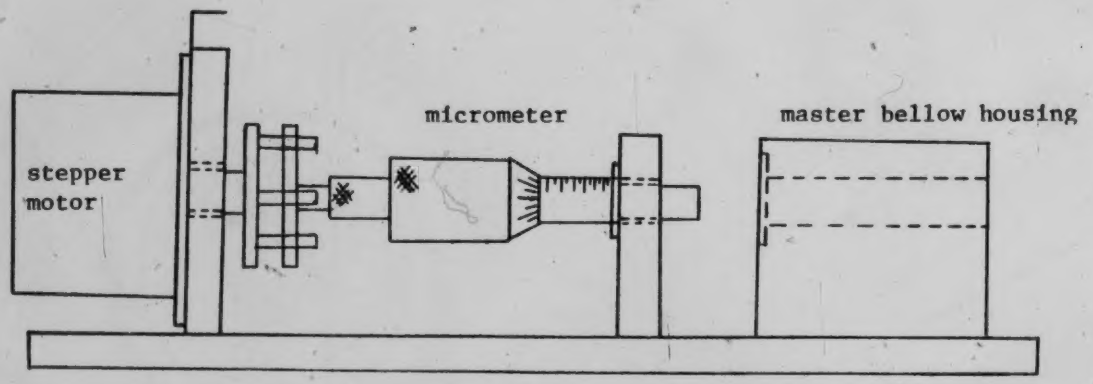

stepper
motor
micrometer
master bellow housing

Figure V.27 Stepper Motor and Micrometer Arrangement
(One Channel Only)

stepper motors, and

(ii) to isolate the microelectrode from any vibration caused by the stepper motors/micrometers arrangements and/or the experimenter.

V.1.5.2.1 HYDRAULIC SYSTEM CALCULATION

The stepper motors selected for the three dimensional microprocessor controlled micro-manipulator system are Hurst RAS 3913-001, 7.5°, 12 volts type. The choice was dependent on the torque requirements and the cost. These motors give 48 steps per revolution.

The micrometers used in the system are non-rotating spindle high precision micrometers. These micrometers give 0.5mm linear movement per revolution.

Since the stepper motors are directly coupled to the micrometers, 48 steps of the stepper motor will cause 0.5mm of linear motion of the micrometer or single step of the stepper motor will give $(\frac{0.5}{48})$mm = 10.4 micrometer of linear motion.

The system uses an 8-bit analog to digital converter. Therefore the total number of digitised levels available to step the motors in either clockwise or counterclockwise direction = 256.

The ± 128 step or ±128 steps configuration is used to ensure the rotation of the motor in both directions.

Number of revolutions of the stepper motor in the clockwise direction $= + \frac{128}{48}$ revs.

$= + 2.67$ revolution

This is equivalent to (2.67x0.5)mm = +1.33mm maximum linear motion at the motor end. Similarly the maximum linear motion in the counterclockwise direction at the motor end = -1.33mm.

The miniature bellows chosen for the hydraulic system have the following specification [64]:

Master Bellow

Inside Diameter = 0.15 inches
Outside Diameter = 0.25 inches
Number of Convolutions = 25
Length = 0.75 inches

Slave Bellow

Inside Diameter = 0.75 inches
Outside Diameter = 1.0 inches
Number of Convolution = 10
Length = 0.75 inches

The major factor determining the choice of the bellows was the cost.

Referring to Figure V.28, assuming that the master bellows is compressed by an amount = ℓ m

Therefore: Volume of fluid displaced from the master bellow = $\frac{\pi}{4} d^2 . \ell \ m^3$ where "d" is the mean diameter of the master bellow.

Since the arrangement is a closed hydraulic system, the volume of fluid displaced from the master bellows should cause an equivalent expansion of the slave bellows.

i.e. Volume of fluid displaced from the master bellows = Volume of fluid accepted by the slave bellows, or

$$\frac{\pi}{4} d^2 \ell \ m^3 = \frac{\pi}{4} D^2 L \ m^3$$

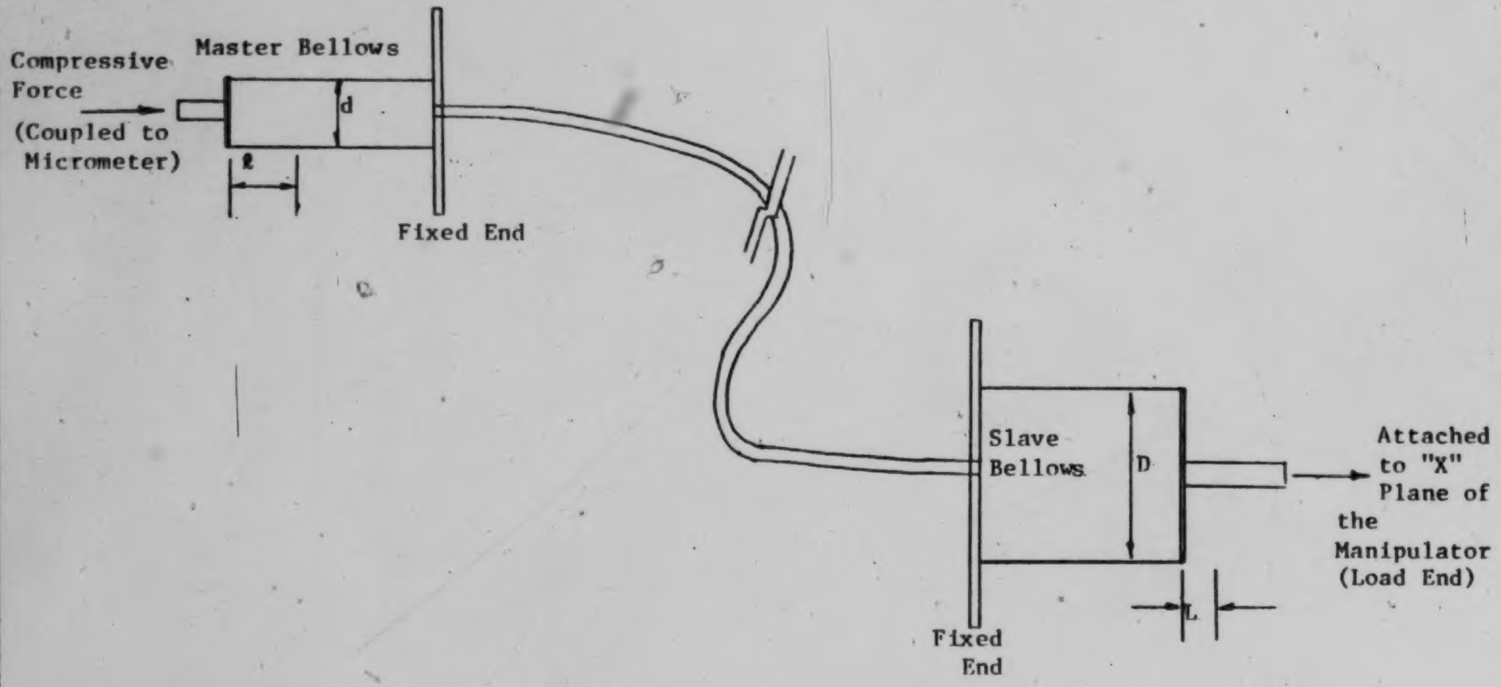

Compressive
Force
(Coupled to
Micrometer)
Master Bellows
d
ℓ
Fixed End
Slave
Bellows
D
L
Fixed
End
Attached
to "X"
Plane of
the
Manipulator
(Load End)

Figure V.28 Master and Slave Bellow Arrangement to Give 19.5 Times Reduction in Linear Motion at Load End

where "D" is the mean diameter of the slave bellow and "L" is the displacement of the free end of the slave bellows.

From above:

$$d^2\ell \quad = \quad D^2L$$

or

$$L \quad = \quad \ell.(\frac{d}{D})^2$$

Mean diameter of the master bellows = 0.2 inches

Mean diameter of the slave bellows = 0.875 inches

This gives:

$$L \quad = \quad \frac{\ell}{19.14}$$

Therefore one complete revolution of the micrometer will cause $(\frac{0.5}{19.14})$mm or 26.1 microns linear motion of the slave bellows per revolution of the stepper motor.

Linear motion of the slave bellows per step of the stepper motor

$$= \frac{26.1}{48}$$

$$= 0.544 \text{ microns}$$

V.1.5.2.2 VIBRATION ANALYSIS

The test table was isolated from the vibrating motion of building structures and vibrating floors by using compressed air balls to give low motion transmissibility as shown in Figure V.29.

The three dimensional manipulator was set up on this table with the rest of the equipment set on a separate table. This arrangement ensures that the vibration of the microelectrode due to the stepping motors/micrometers arrangement and the experimenter is kept to the minimum. In this analysis it is assumed that the vibrating motion of the building structures and vibrating floors have no effect on the microelectrode. The effect of the manipulator mass and the damping force on microelectrode vibration are considered in this analysis.

Any system in which masses are coupled by non-rigid members are capable of vibrating. If the system is disturbed for a fixed duration it will continue to vibrate after the disturbance has been removed. Such a vibration is described as "free" vibration. In practice no such system exists since forces which oppose the motion, usually called "damping" or "dissipative" forces cause the vibration to decay to zero. Additionally, forces which tend to cause or to increase the vibration, usually are called disturbing forces, may tend to act as well.

Damping forces in a mechanical system can arise from numerous sources. Most common of these forces are:

(i) hysteresis in solid materials,

(ii) resistance due to motion of fluid which may be called fluid damping, and

(iii) friction between dry material which may be called coulomb damping.

V.1.5.2.2.1 DAMPED VIBRATION

Any one plane of the three dimensional hydraulically controlled manipulator can be considered as shown in Figure V.30. The damping is represented by the dashpot which provides fluid damping and also it is

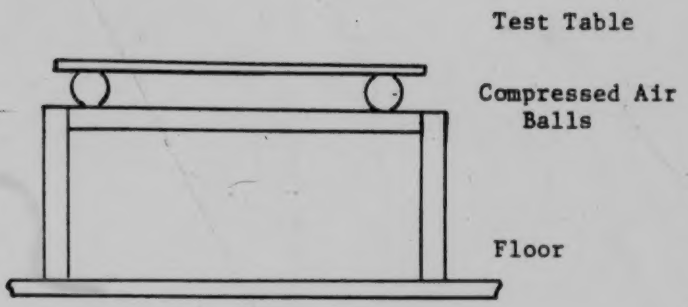

Test Table
Compressed Air Balls
Floor

Figure V.29 Test Table Arrangement

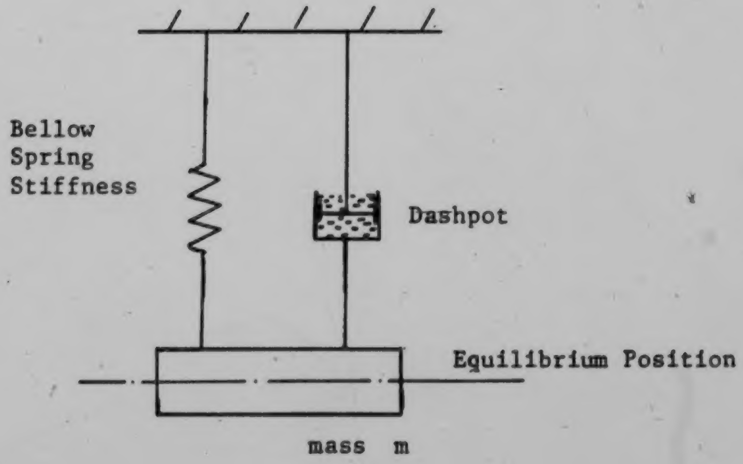

Bellow Spring Stiffness
Dashpot
Equilibrium Position
mass m

Figure V.30 Representation of a Three-Dimensional Manipulator in Any One Plane With Viscous Damping (Hydraulic System)

assumed that only guided vertical motion is permitted. It is also assumed in this analysis that the positive direction of the x-axis is upwards. Let the mass of the platform be "m", the stiffness of the bellow spring be "λ" and the damping constant of the fluid damping system be "f". Let the mass be displaced from its equilibrium position and at some subsequent time let the displacement and velocity of the mass be "+x" and "$+\dot{x}$" respectively. At this instant then the forces acting the mass "m" are as shown in Figure V.31.

The gravitional force = $-mg$

The total force due to Spring = $+(mg-\lambda x)$

The force due to the damping system = $-f\dot{x}$

Therefore, the net force on mass "m" = $-f\dot{x}-\lambda x$

From Newton's Second Law of motion we can write

$$\ddot{x} + \frac{f}{m}\dot{x} + \frac{\lambda x}{m} = 0 \qquad (1)$$

and it is also known that

$$\frac{\lambda}{m} = w_n^2$$

where w_n = natural radiancy of an undamped system

This gives

$$\ddot{x} + \frac{f}{m}\dot{x} + w_n^2 x = 0 \qquad (2)$$

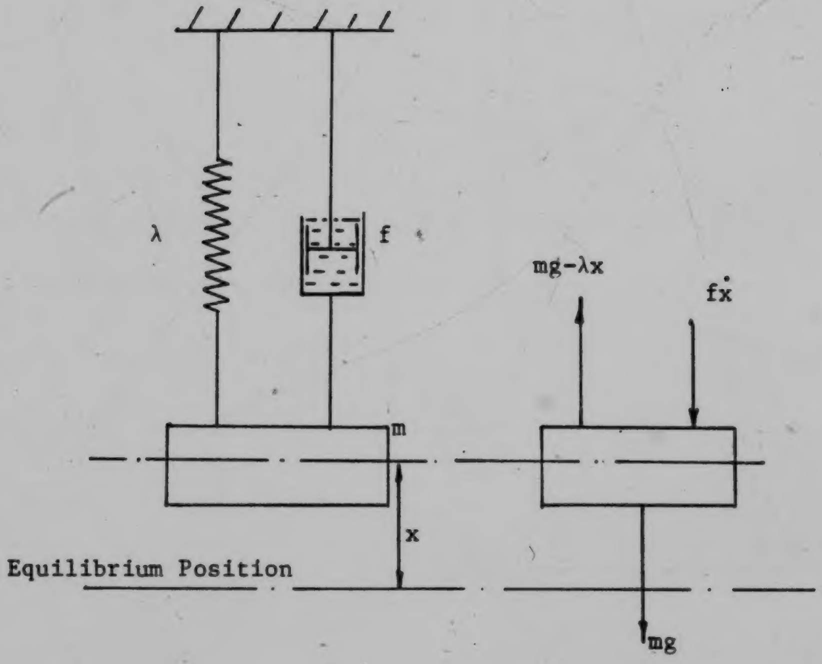

λ
f
m
x
Equilibrium Position
mg-λx
$f\dot{x}$
mg

Figure V.31 Spring-Mass System With Damping

The solution of this second order differential equation will be of the form $x = Ae^{\alpha t}$, which when substituted in the above equation gives

$$A\alpha^2 e^{\alpha t} + \frac{f}{m} A\alpha e^{\alpha t} + w_n^2 A e^{\alpha t} = 0 \qquad (3)$$

or

$$\alpha^2 + \frac{f}{m}\alpha + w_n^2 = 0 \qquad (4)$$

Solving this equation for α gives

$$\alpha = -\frac{f}{2m} \pm \sqrt{\left[\left(\frac{f}{2m}\right)^2 - w_n^2\right]} \qquad (5)$$

It can be shown that

$$\frac{f}{m} = 2cw_n$$

where damping ratio "c" $= \frac{f}{fc}$

and fc = damping constant for critically damped system

this gives

$$\alpha = -cw_n \pm w_n\sqrt{(c^2-1)} \qquad (6)$$

we can now consider the three particular cases arising from this equation.

For C>1 it can be shown that

$$x = A_1e^{\alpha_1 t} + A_2e^{\alpha_2 t} \qquad (7)$$

for C<1 it can be shown that

$$x = A_3e^{-cw_n t} \cos\{w_n\sqrt{1-c^2}t + \phi\} \qquad (8)$$

and for

C=1 it can be shown that

$$x = A_4e^{-w_n t} + A_5t\, e^{-w_n t} \qquad (9)$$

where A_1, A_2, A_3, A_4, A_5 and ϕ are arbitrary constants depending on the initial condition.

Figure V.32 shows the response of the damped spring-mass system released from a displacement at zero time. From this response it can be seen that as the damping ratio "c" increases, the vibration of the system decays faster. Since the damping factor "c" is inversely proportional to the mass of the system it can thus be concluded that the larger the mass the longer it will take for vibration to decay to zero and also the amplitude of vibration (displacement of the mass) decreases with decrease in the mass of the system.

V.1.5.2.2.2 **FORCED VIBRATION**

Let us now consider the behaviour of the system when it is subjected to a disturbing force. This force may be simple or complex

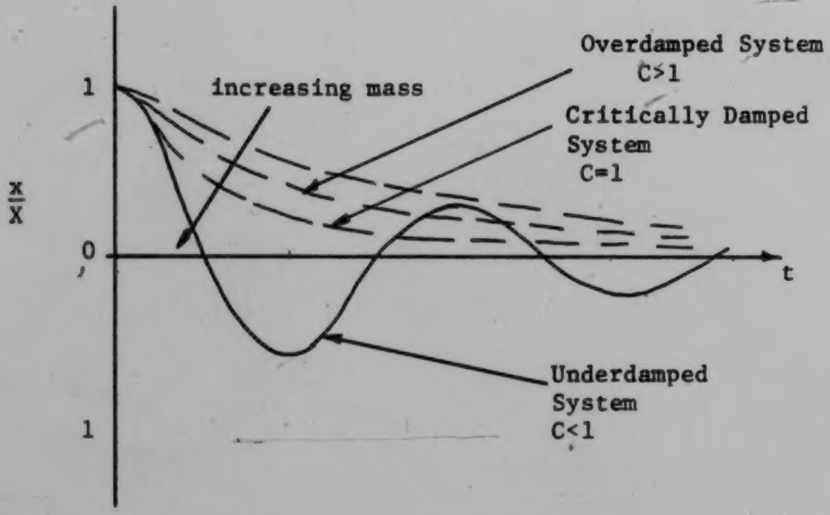


Figure V.32 Response of a Damped Spring-Mass System Released from a Displacement at Zero Time

in nature, and it is impossible to deal with all the variants. In a practical application, the three dimensional manipulator will be subjected to a suddenly applied force of constant amplitude.

Let the force "F" be suddenly applied at $t=0$ to a mass when it is at rest. Under this condition it can be shown that

$$\ddot{x} + 2c\, w_n \dot{x} + w_n^2 x = \frac{F}{m} \qquad (10)$$

if the system damping is sub-critical the transient solution is given by

$$x = A_3 e^{-cw_n t} \cos\{w_n \sqrt{1-c^2}\, t + \phi\} \qquad (11)$$

There are several ways of finding the particular integral but perhaps the easiest is to consider what will be the state of affairs when transient vibration has died away. Alternatively we can guess a form of "x" similar to the righthand side of the equation, which is a constant, thus we can assume

$$x = A$$

if so $\dot{x} = \ddot{x} = 0$

Substituting in Equation 10 gives

$$w_n^2 A = \frac{F}{m}$$

or

$$A = \frac{F}{mw_n^2}$$

$$= \frac{F}{\lambda}$$

thus the complete solution is

$$x = A_3 e^{-cw_n t} \cos(w_n \sqrt{1-c^2}\, t + \phi) + X_s \qquad (12)$$

where $X_s = \frac{F}{\lambda}$

Since the mass started from rest

$$x_{t=0} = A_3 \cos \phi + X_s = 0$$

$$\dot{x}_{t=0} = -cw_n \cos \phi - w_n \sqrt{1-c^2} \sin \phi = 0$$

whence we obtain the expression

$$\frac{x}{X_s} = 1 - \frac{e^{-cw_n t}}{\sqrt{1-c^2}} \cos\{w_n \sqrt{(1-c^2)}\, t + \tan^{-1}\left(\frac{-c}{\sqrt{(1-c^2)}}\right)\} \qquad (13)$$

Though this expression, as is often the case with vibrating systems, appears to be rather complicated, it can be easily demonstrated that it fits the known facts. When t is large the expression reduces to

$$x = X_s = \frac{F}{\lambda}$$

while if c is small we see that the early stages of the vibration are

$$x = X_s(1-\cos w_n t)$$

or

$$x = \frac{F}{\lambda}(1 - \cos w_n t)$$

Figure V.33 shows the response of the damped spring-mass system when a force "F" is suddenly applied at zero time.

From the analysis, Figure V.32 and Figure V.33, it can be seen that as:

(i) the mass of the manipulator increases, it takes longer for the vibration to decay to zero,

(ii) the amplitude of vibration increases as the mass of the manipulator increases,

(iii) the damping force increases the vibration of the manipulator decays to zero faster.

From the above analysis it can be concluded that:

(i) it is very important that in designing the three dimensional manipulator the mass should be kept as small as possible, and

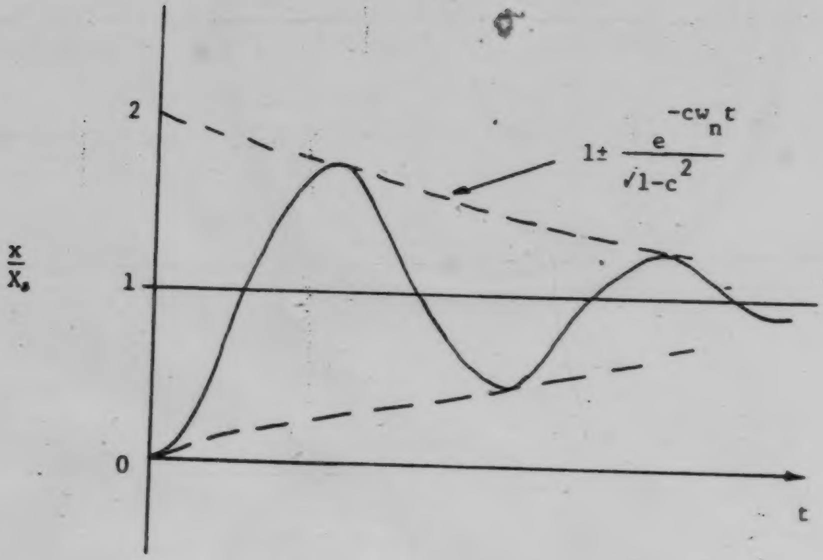


Figure V.33 Response of Damped Spring-Mass System When a Force "F" is Suddenly Applied at Zero Time ($c<1$)

(ii) using hydraulic system with high damping force and flexible coupling between the three dimensional manipulator and the stepper motors/micrometers arrangement, the microelectrode can be isolated of vibration due to stepper motors/micrometers arrangement.

V.1.5.2.3 THE HYDRAULIC SYSTEM ARRANGEMENT

The three micrometers, driven by the three stepper motors, are directly coupled to the 0.25" diameter by 0.75" long master bellows. The outputs of these three master bellows are linked to the three 1.0" diameter by 0.75" long slave bellows, via flexible polythlyene tube. Hydraulic fluid fillers had to be designed and attached to the master bellows. Air bleeders at the sealed end of the master and slave bellows were also installed. This arrangement enables air to be bled out while filling the hydraulic system. The detailed hydraulic arrangement is shown in Figure V.34.

V.1.5.3 THREE DIMENSIONAL HYDRAULIC MANIPULATOR WITH MICROELECTRODE HOLDER

The three dimensional hydraulic manipulator was designed to convert the linear motion of the precision non-rotating spindle micrometers to the three dimensional linear motion of the microelectrode attached to the manipulator. The manipulator is linked to the three micrometers via a closed hydraulic system. This arrangement overcomes any vibrational problems associated with the stepper motors, micrometers or the experimenter.

The three dimensional manipulator was designed using aluminum for light weight. The three 1.0" diameter slave bellows are mounted on the

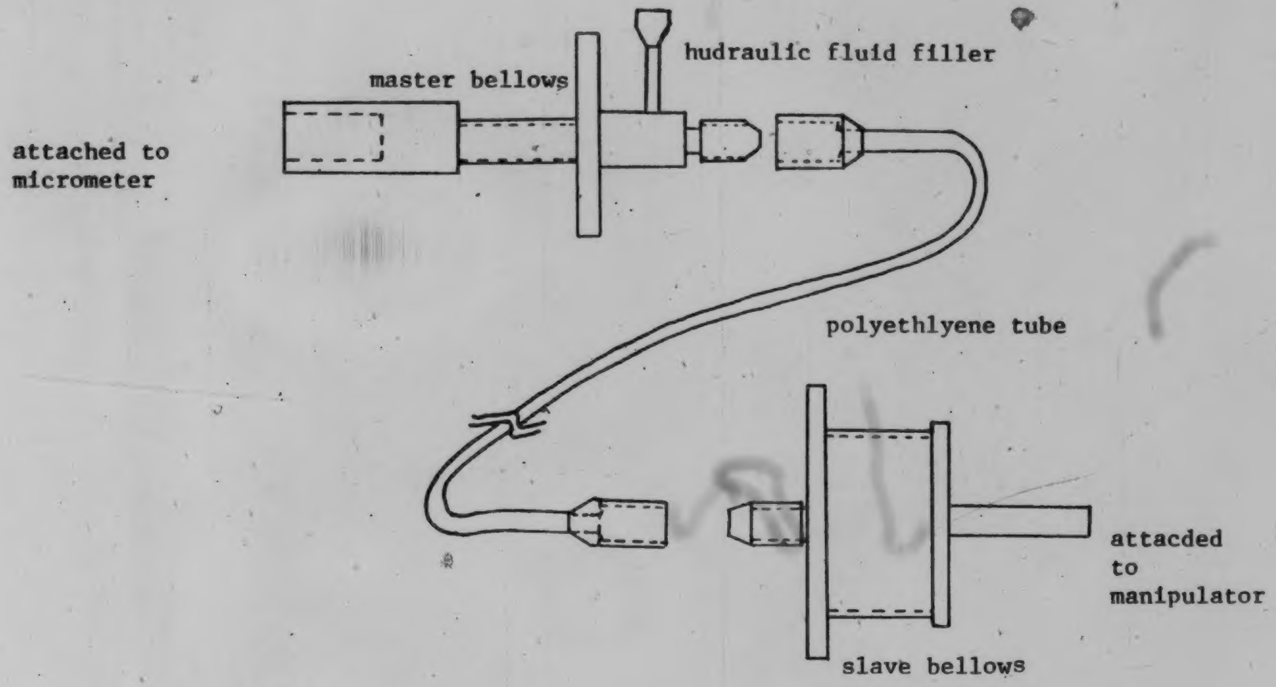

attached to micrometer
master bellows
hudraulic fluid filler
polyethlyene tube
slave bellows
attacded to manipulator

Figure V.34 Hydraulic System Arrangement

three dimensional manipulator in the "X", "Y" and "Z" plane. The free end (sealed end) of the "X" and "Y" slave bellows are linked to the "X" and "Y" platforms to give linear motion in sub-microns in the X-Y plane. To reduce friction the moving platforms were assemblesd using six miniature linear bearings. The "Z" bellows was mounted vertically on the "Y" platform to give sub-micron movement in the "Z" direction. The microelectrode holder is attached to the free end of the "Z" slave bellow using miniature linear bearing and a low friction mechanical link. The detailed drawing of the three dimensional hydraulic controlled manipulator with microelectrode holder is shown in Figure V.35.

The complete arrangement is attached to the "Z" control of a standard magnetic base manipulator stand.

V.2 SOFTWARE

The software primarily consists of:

(i) A main program, and

(ii) An interrupt routine.

The bulk of the main program deals with the control of the three stepper motors via joystick whereas the interrupt routine mainly deals with the control of the stepper motors via keyboard.

V.2.1 MAIN PROGRAM

The main program occupies approximately two kilobytes of EPROM and resides in EPROM 1. The memory map shown in Figure V.36 and Figure V.37 show the device and main program software addresses. The structured flow chart describing the main program is shown in Figure V.38. The main program software mainly consists of:

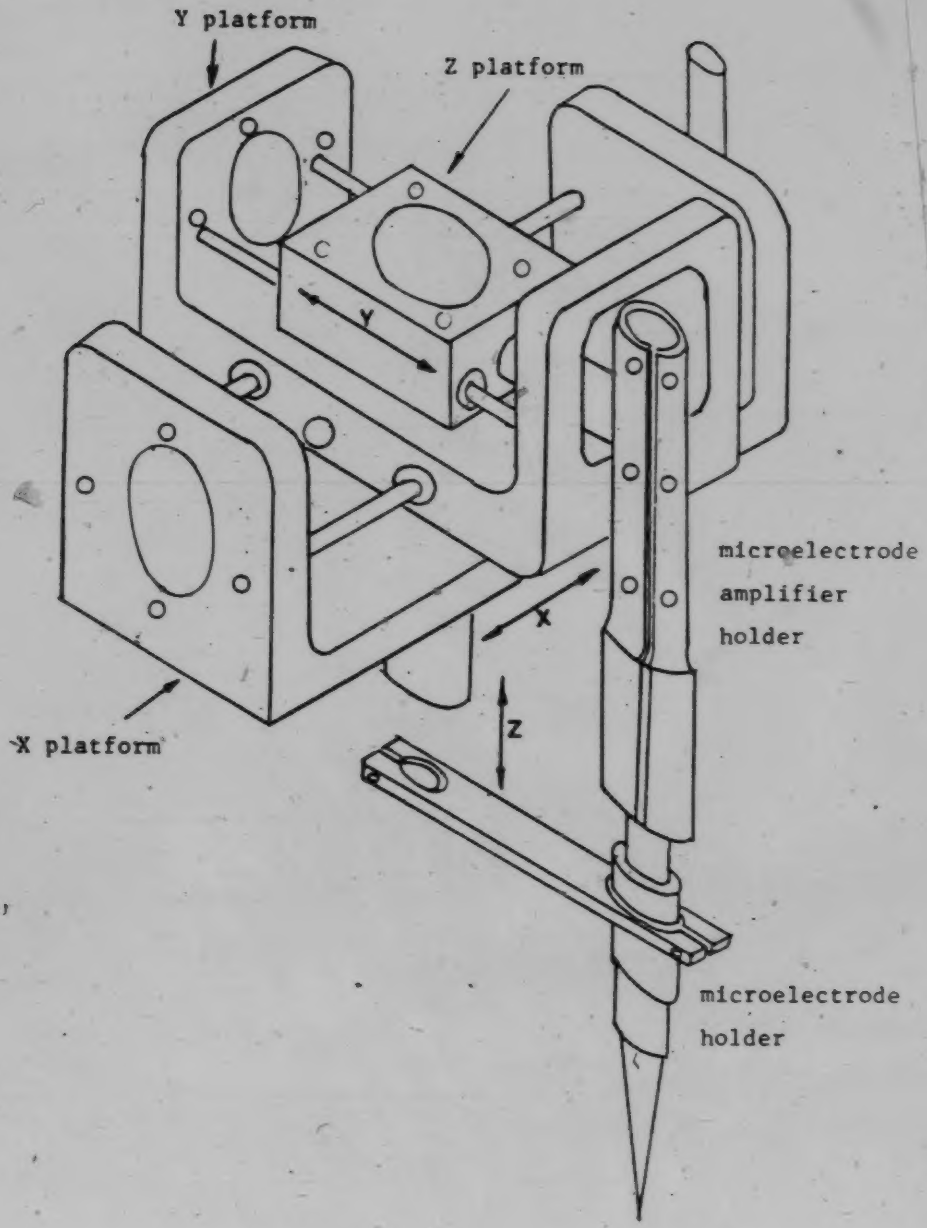

Y platform
Z platform
Y
X
Z
microelectrode
amplifier
holder
X platform
microelectrode
holder

Figure V.35 Three Dimensional Manipulator With Microelectrode Holder

Address	Device Description			
8000	PIA1	Port A	PA0-PA3	Input Port Keyboard
8003			PA4-PA7	Output Port Control Lines
		Port B	Output Port	
			PB0-PB3	Stepper Motor "X"
			PB4-PB7	Stepper Motor "Y"
9000	PIA2	Port A	Input Port	
9003			PA0-PA7	Analog-to-Digital Converter
		Port B	Output Port	
			PB0-PB3	Stepper Motor "Z"
			PB4-PB7	Control Lines
C000	ICM7218	Universal LED Driver		
		Display "X" and "Y"		
C008		Display "Z" and Cell Potential		
D000	4 Kilobytes RANDOM Access memory			
DFFF				
E000	Programmable Timer			
E007				
E008	Asychronous Communication Interface Adaptor			
E00A	ACIA (Host and Terminal)			
F000	4 Kilobytes EPROM			
FFFF				

Figure V.36 Memory Map - Device Locations

Address	Description
FFFE	RESET VECTOR
FFF8	INTERRUPT VECTOR
FF96	SUBROUTINES, SEQX, SEQY, SEQZ, SCAN, HESXDEC, DISPLZ, DISPVZ, READ ZI, READ VT,
FDA2	STSPX/Y, MOTOC/D, MCONTA
FDA1	
	JOYSTICK CONTROL ROUTINE MOTORS "X", "Y" and "Z"
F900	
F8FE	
	SYSTEM INITIALISATION AND SET-UP ROUTINE
F800	

Figure V.37 Main Program Software Location

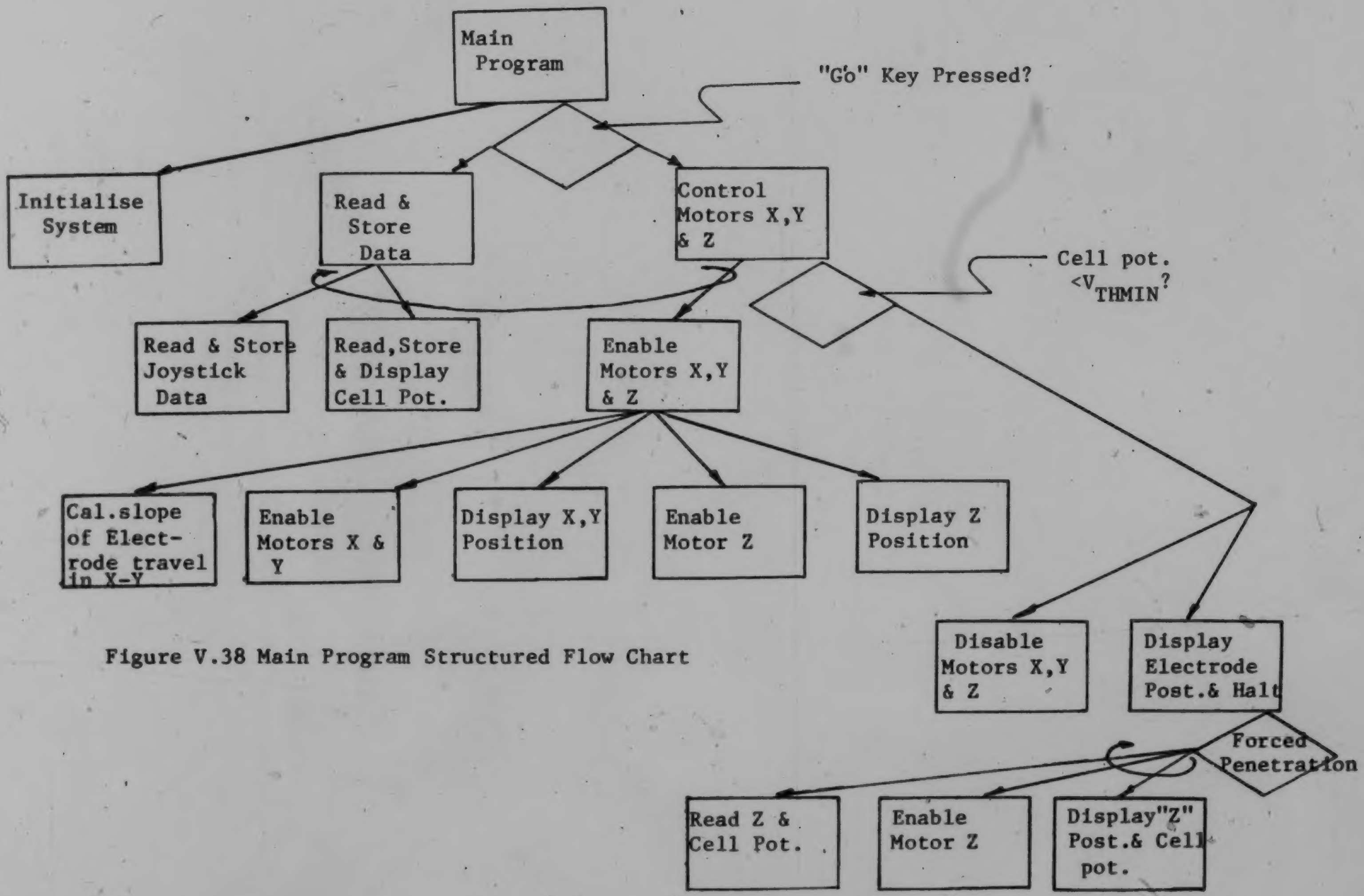

Main Program
"Go" Key Pressed?
Initialise System
Read & Store Data
Control Motors X,Y & Z
Cell pot. <V THMIN?
Read & Store Joystick Data
Read,Store & Display Cell Pot.
Enable Motors X,Y & Z
Cal.slope of Electrode travel in X-Y
Enable Motors X & Y
Display X,Y Position
Enable Motor Z
Display Z Position
Disable Motors X,Y & Z
Display Electrode Post.& Halt
Forced Penetration
Read Z & Cell Pot.
Enable Motor Z
Display"Z" Post.& Cell pot.

Figure V.38 Main Program Structured Flow Chart

(i) The system initialisation module.

(ii) The read and store data module, and

(iii) The motors "X", "Y" and "Z" control module.

V.2.1.1 SYSTEM INITIALISATION MODULE

During the initialisation routine interrupts are disabled and the user and system stacks are initialised to $DCFF and $DFFF respectively. The two parallel interface adaptors (PIA's) are configured as follows:

Port A of Parallel Interface Adaptor 1 (PIA1) is configured as: PA0-PA3-input port

PA4-PA7-output port

Port B is set as an output port to drive the stepper motors "X" and "Y". Parallel Interface Adaptor 2 (PIA2) is configured as:

Port A PA0-PA7-input port to interface analog processing module, and

Port B PB0-PB7-an output port to drive stepper motor "Z", display, and other control displays.

The control lines CA1 on Parallel Interface Adaptor 1 (PIA1) is set for a low-to-high transition and bit "0" of the Parallel Interface Adaptor 1(PIA1) is set to enable the Parallel Interface Adaptor interrupt.

All displays are initialised to zero and the counters are cleared to connect channel "X" of the joystick to the analog-to-digital converter. Upon completion of the initialisation routine the Motorola MC6809 microprocessor regular interrupt is enabled and a one second buzzer sounded to indicate completion of the initialisation routine.

The system goes into "stand-by" mode waiting for the "GO" key on the keyboard to be pressed. The detailed flow chart describing the initialisation routine is shown in Figure V.39.

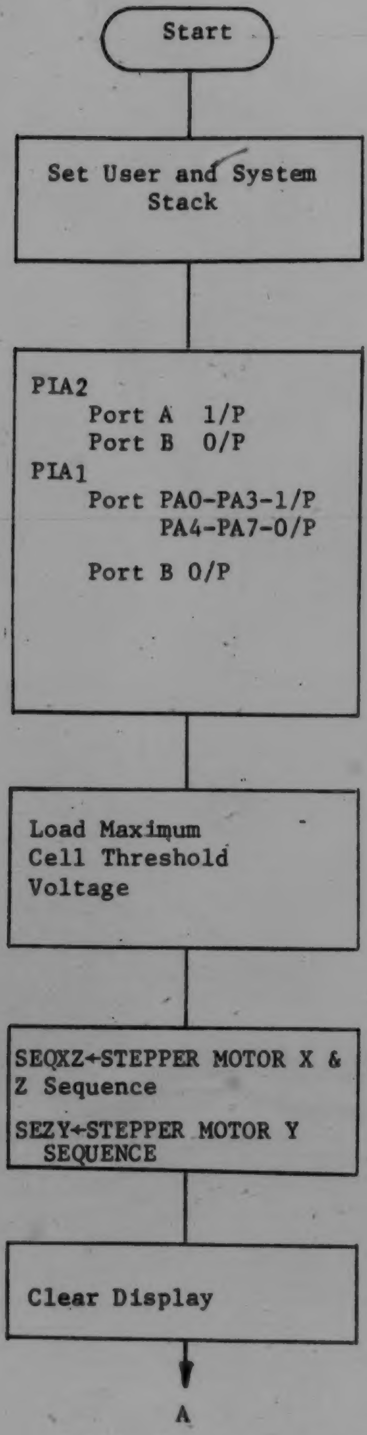
V.1.2.2 READ AND STORE DATA MODULE

Once the "GO" key on the keyboard is pressed, the system leaves the "standby" mode and goes on to read and store the joystick setting and the intracellular potential. The flow chart describing the above module is shown in Figure V.40.

V.2.1.3 MOTORS "X", "Y", AND "Z" CONTROL MODULE

This module deals with the control of the motors "X", "Y" and "Z" via joystick. The system checks if the intracellular potential is less than the cell threshold voltage (this indicates that the microelectrode has already penetrated the tissue). For the intracellular potential greater than the cell threshold voltage the system continues to control stepper motors "X" and stepper motor "Y" in addition to stepper motor "Z". The motors are rotated in either a clockwise or counterclockwise direction depending on the joystick setting. The stepping rate is in either constant speed mode or ramp speed mode depending on the number of steps to be taken. This stepping sequence ensures that the desired position is reached quickly. The actual microelectrode position in the "X", "Y" and "Z" directions are displayed after each step. Once the motors "X" "Y" and "Z" have taken the required number of steps the input is scanned again and the routine repeated.

For intracellular potential less than the threshold cell voltage, the system disables the stepper motor "X", "Y" and "Z", displays the present "Z" position and the intracellular potential, enables a one


Start
Set User and System Stack
PIA2
Port A 1/P
Port B 0/P
PIA1
Port PA0-PA3-1/P
PA4-PA7-0/P
Port B 0/P
Load Maximum Cell Threshold Voltage
SEQXZ←STEPPER MOTOR X & Z Sequence
SEZY←STEPPER MOTOR Y SEQUENCE
Clear Display
A

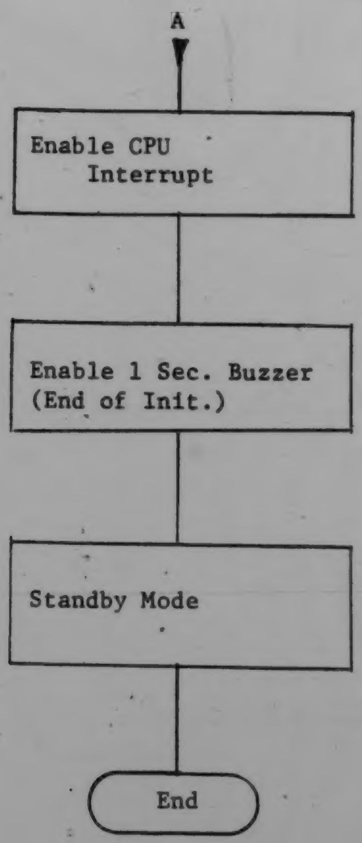
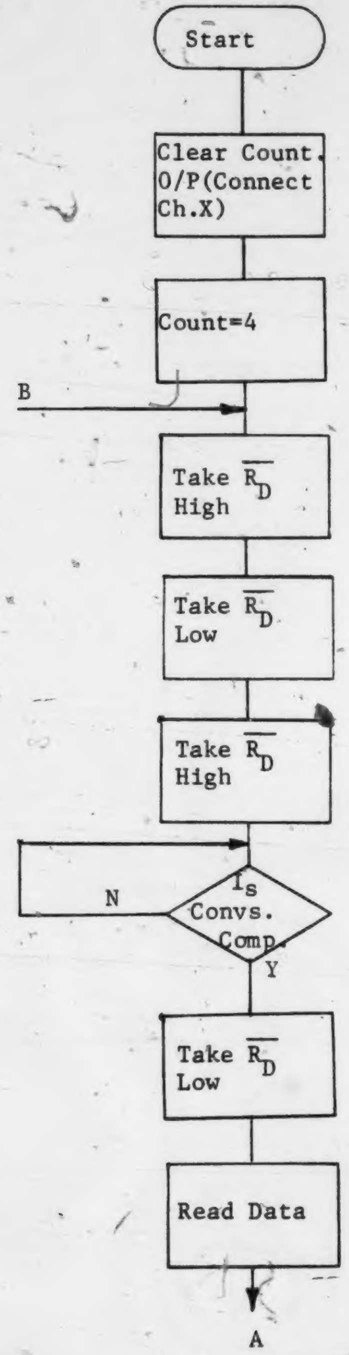

A
Enable CPU Interrupt
Enable 1 Sec. Buzzer (End of Init.)
Standby Mode
End

Figure V.39 Initialisation Routine Flow Chart


Start
Clear Count. O/P(Connect Ch.X)
Count=4
B
Take $\overline{R_D}$ High
Take $\overline{R_D}$ Low
Take $\overline{R_D}$ High
Is Convs. Comp.
N
Y
Take $\overline{R_D}$ Low
Read Data
A

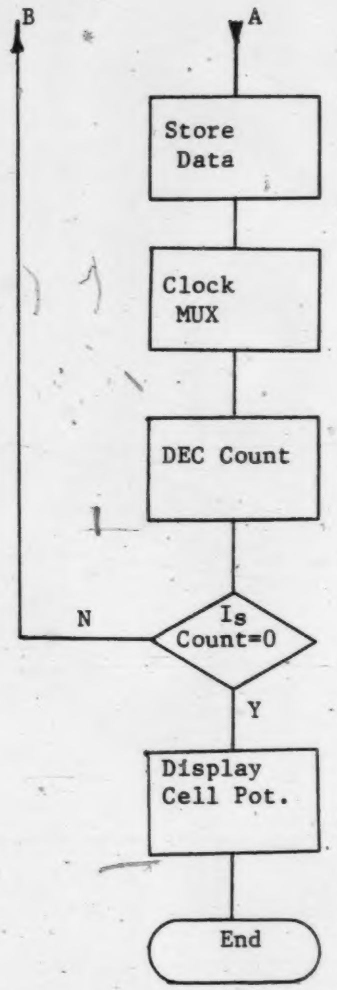

B
A
Store Data
Clock MUX
DEC Count
N
Is Count=0
Y
Display Cell Pot.
End

Figure V.40 Read and Store Data Routine Flow Chart

second audible/visual alarm (indicating that threshold cell voltage is reached), and goes into low power "HALT" mode. The system can be forced out of this mode either via a keyboard mode control or by pressing the "Force Penetration" key (.P) on the keyboard. This enables the stepper motor "Z" to be controlled via joystick.

The detailed flow chart describing the main program routine is shown in Appendix B, Figure B.1.

V.2.2 INTERRUPT ROUTINE

The interrupt routine occupies approximately two kilobytes of EPROM and resides in EPROM 2. The detailed interrupt routine software locations is shown in Figure V.41.

This routine deals with the control of the stepper motors via the keyboard. The desired microelectrode position in either "X", "Y" or "Z" direction is entered under keyboard control. Any error made in entry can be corrected by pressing the "cancel" key and re-entering the desired position. Once the "enter" key is pressed, the system converts the desired position into the number of steps to be taken by the stepper motor, determines the direction of rotation and enables the selected stepper motor in either constant velocity mode or ramp mode depending on the number of steps to be taken. On return from the interrupt the system goes into "stand-by" mode and remains in this state until the "GO" key on the keyboard is pressed.

The threshold voltage entry can also be altered by entering the new threshold voltage via the keyboard.

On completion of the experiment the microelectrode can be returned to the "Home" (initial microelectrode position at system

Address	Description
F7DD	
	SUBROUTINES BEDHEX, RCONVT, DISPZV, DISPXY, READK, RATIO, DELAY, MCOUNT, DISPLI, DISPLZ, SEXT, SETY, SETZ, DSPKY, DSPZV, SEQXK, SEQYK, SEQZK, MOTOA, MOTOB
F5DE	
	"HOME" ROUTINE
F3DA	
	THRESHOLD VOLTAGE ENTRY
F380	
	STEPPER MOTORS "X", "Y", AND "Z" CONTROL ROUTINE VIA KEYBOARD
F000	

Figure V.41 Interrupt Routine Memory Map
(Software Locations)

switch on) position by pressing the "home" key on the keyboard. It is important that the microelectrode be returned to its initial position otherwise the mechanical bellows will remain in compression or expansion when the system is switched off and can be damaged when the system is operated next time.

The structured flow chart describing the interrupt routine is shown in Figure V.42. The interrupt routine software mainly consists of:

(i) The stepper motor "X" control module.
(ii) The stepper motor "Y" control module.
(iii) The stepper motor "Z" control module.
(iv) The "Home" module.
(v) The threshold voltage entry module.

The detailed flow chart describing the interrupt routine is shown in Appendix B, Figure B.2.

V.2.3 KEYBOARD DATA ENTRY

All parameters for effective control of the manipulator can be entered via the keyboard. This data entry routine operates in the interrupt mode. To get into the interrupt mode the "K" key on the keyboard is pressed. Since the control line CA1 of the Parallel Interface Adaptor 1 (PIA1) is tied to the data available line on the keyboard encoder, it causes bit seven of the control register to be set thus enabling the Parallel Interface Adaptor 1 (PIA1) interrupt. The keyboard is the only source of interrupt; therefore the program does not have to test bit 7 of the Parallel Interface Adaptor 1 (PIA1). The detailed flow chart showing the data entry routine is shown in

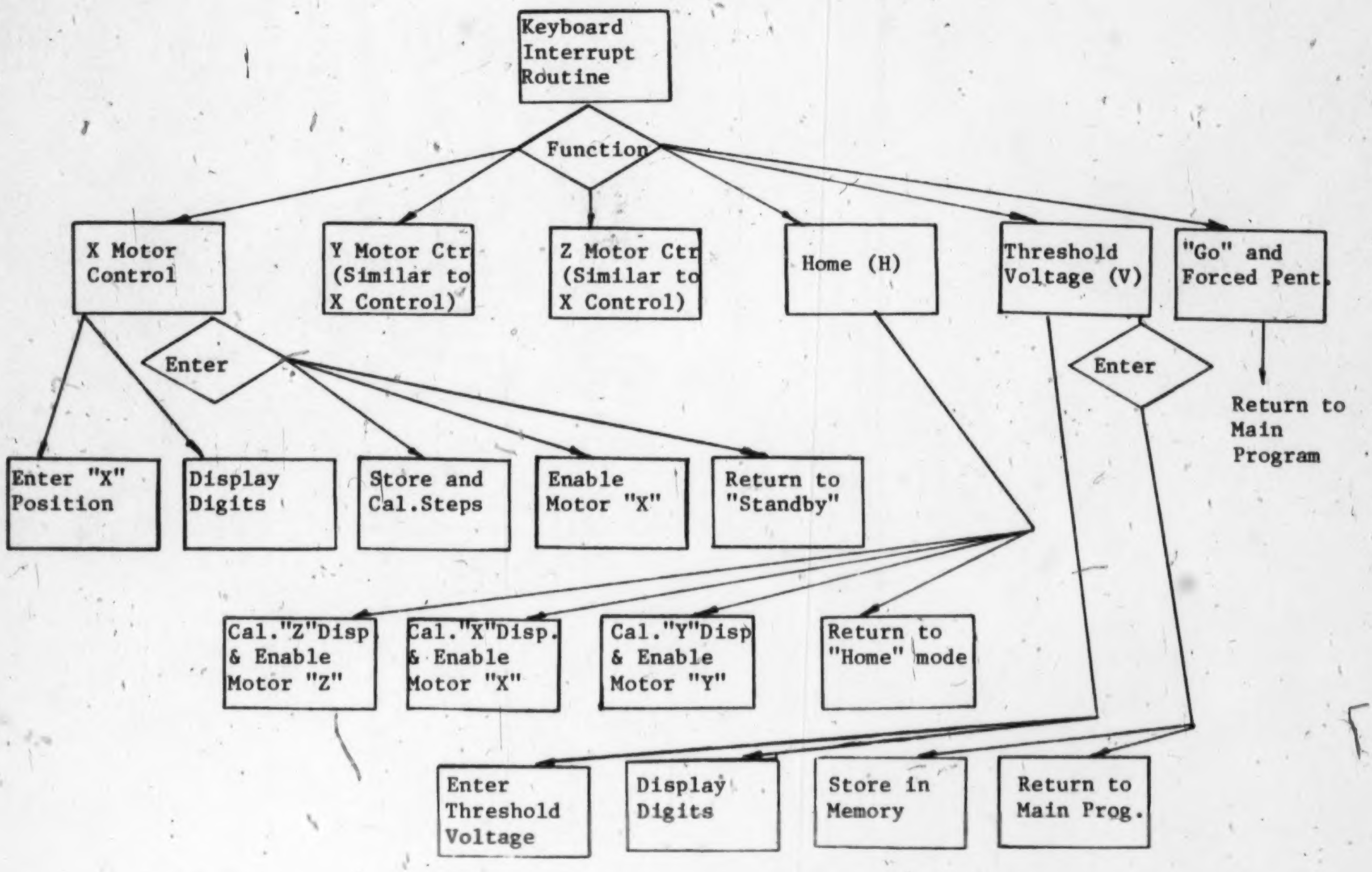

Keyboard Interrupt Routine
Function
X Motor Control
Y Motor Ctr (Similar to X Control)
Z Motor Ctr (Similar to X Control)
Home (H)
Threshold Voltage (V)
"Go" and Forced Pent.
Return to Main Program
Enter
Enter "X" Position
Display Digits
Store and Cal.Steps
Enable Motor "X"
Return to "Standby"
Cal."Z"Disp & Enable Motor "Z"
Cal."X"Disp. & Enable Motor "X"
Cal."Y"Disp & Enable Motor "Y"
Return to "Home" mode
Enter
Enter Threshold Voltage
Display Digits
Store in Memory
Return to Main Prog.

Figure V.42 Interrupt Routine - Structured Flow Chart

Figure V.43. Once in the keyboard mode, the function is selected by depressing the particular function key (i.e. "X", "Y", "Z", V_{TH}, HOME (H)). Once the function has been selected then the display is cleared and the four digits can be entered with the most significant digit (MSD) first. The digits are displayed as entered. Once all four digits have been entered then the data can be either entered and transferred for storage and further calculations by depressing the "Enter" key or cancelled by pressing the "Clear" key and all four digits re-entered.

V.2.4 STEPPER MOTOR CONTROL

The two basic modes of operation of stepper motor are:

(i) Constant speed mode, and

(ii) acceleration/Deceleration mode.

In constant speed mode the stepper motors cover N steps at a constant stepping rate of 2 steps/sec. This stepping rate is the so-called "start-stop" rate at which the motor starts, stops and reverses on each step. This ensures that the motor does not miss any step at start, nor does it overshoot the mark on stopping.

The "start-stop" rate is usually very low in this case 2 steps/sec. It will not matter much if "N" the number of steps to be taken is low. However, if N, the number of steps to be taken, is large, it will take an inordinately long time for the motor to go through the "N" steps. To overcome this difficulty it is desirable to operate the motor at a so-called "slewing rate" which is much higher than the "start-stop" rate. However there is a basic difficulty in operating the motor at a slewing rate, viz. we cannot apply input

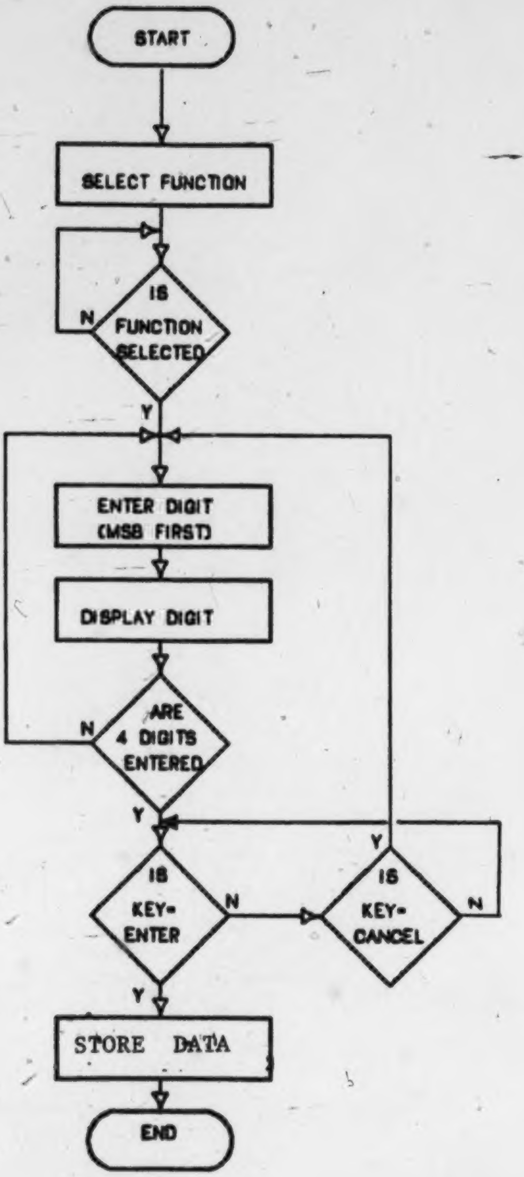

START
SELECT FUNCTION
IS FUNCTION SELECTED
N
Y
ENTER DIGIT (MSB FIRST)
DISPLAY DIGIT
ARE 4 DIGITS ENTERED
N
Y
IS KEY-ENTER
N
Y
IS KEY-CANCEL
Y
N
STORE DATA
END

Figure V.43 Keyboard Data Entry Routine Flow Chart

pulses at a slewing rate to a motor at rest, because the motor will miss several steps before it started slewing. Similarly if the motor were stepping at slewing rate and if we suddenly stop applying pulses the motor will overshoot the mark by several steps before coming to a stop.

To overcome this dilemma, the following scheme is adopted:

(i) The motor is started at a stepping rate somewhat below the "start-stop" rate so that the motor starts off smoothly without missing any steps.

(ii) The motor speed is then increased to the slewing rate.

(iii) The motor is caused to complete the major portion of N steps at the slewing rate.

(iv) When the end approaches, the motor speed is decreased down to the "start-stop" rate.

(v) The motor operation is stablised at the "start-stop" rate before it stops so that the motor halts after exactly N steps without overshooting

This scheme is shown in Figure V.44.

Algorithms for the two modes of operation are described by flow charts shown in Figures V.45 and Figure V.46.

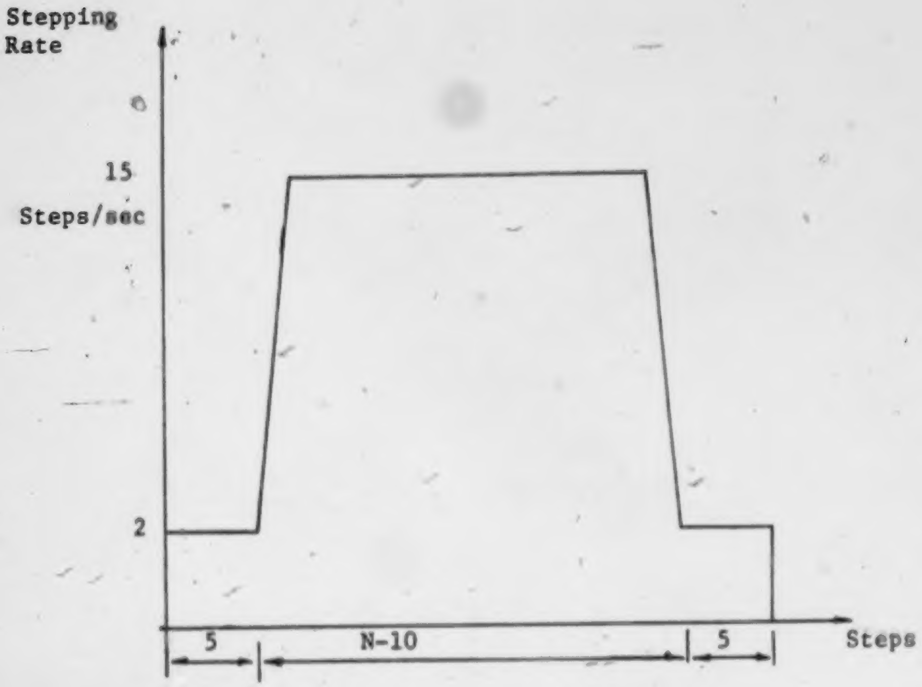


Figure V.44 Stepper Motor Stepping Sequence

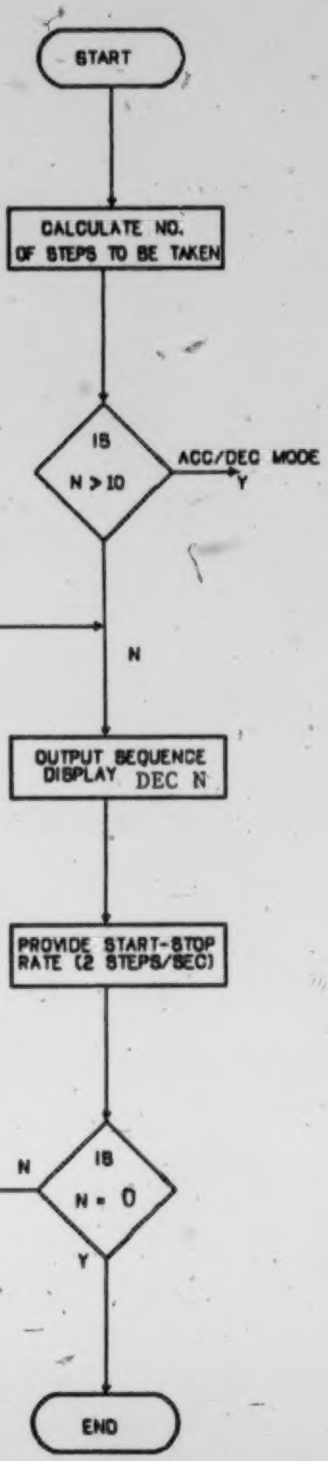

START
CALCULATE NO. OF STEPS TO BE TAKEN
IS N > 10
ACC/DEC MODE
Y
N
OUTPUT SEQUENCE DISPLAY DEC N
PROVIDE START-STOP RATE (2 STEPS/SEC)
IS N = 0
N
Y
END

Figure V.45 Constant Speed Mode Flow Chart

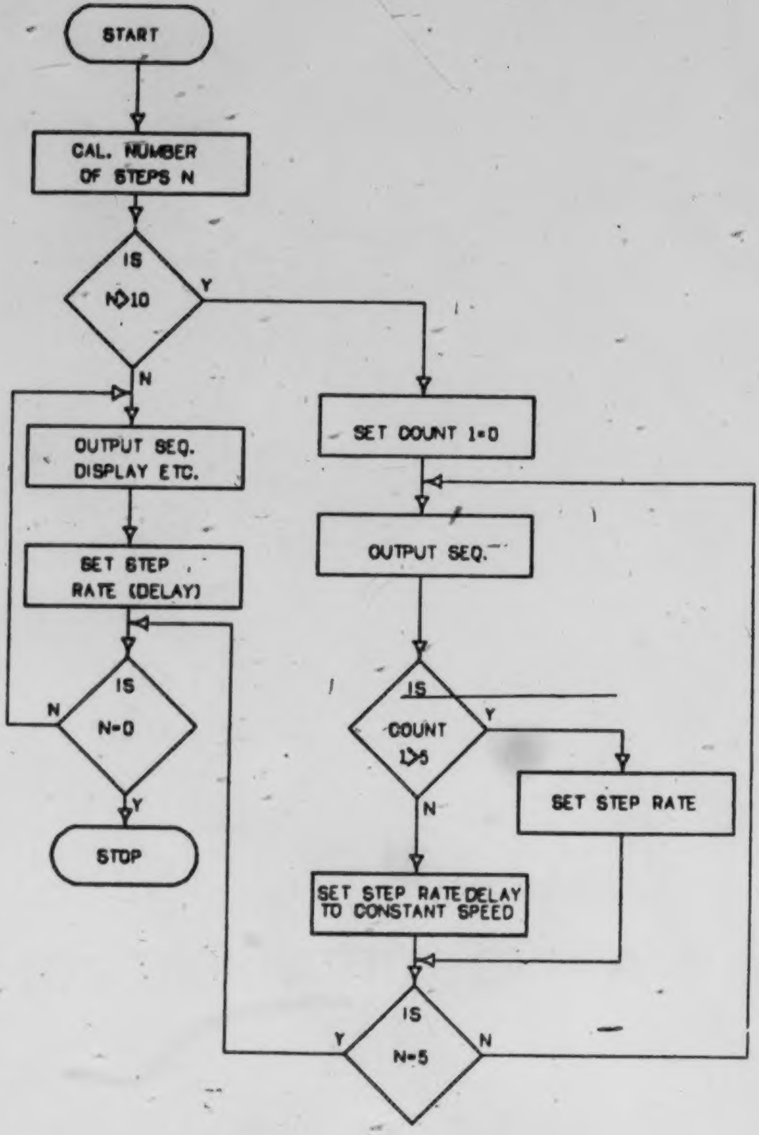

START
CAL. NUMBER OF STEPS N
IS N>10
Y
N
OUTPUT SEQ. DISPLAY ETC.
SET STEP RATE (DELAY)
IS N=0
N
Y
STOP
SET COUNT I=0
OUTPUT SEQ.
IS COUNT I>5
Y
N
SET STEP RATE
SET STEP RATE DELAY TO CONSTANT SPEED
IS N=5
Y
N

Figure V.46 Ramp Speed Mode Flow Chart

CHAPTER VI

SYSTEM PERFORMANCE

In this chapter the performance of the final implementation of the three-dimensional microprocessor controlled micro-manipulator is described. After implementation, if the performance of the particular design does not fulfill its requirements, one must try an alternate implementation or decide on a new set of specifications. If the requirements of a design cannot be met by alternate implementations or changes in the specifications, then the requirements must be relaxed.

VI.1 HARDWARE

VI.1.1 MICROCOMPUTER SYSTEM AND ASSOCIATED INTERFACE

All hardware components in the microcomputer system, stepper motors control, analog processing module, keyboard and display system and the probe amplifier have been tested directly or indirectly and in the final design no malfunction has been detected. Wherever possible, hardware components have been tested before being used within the system. During system development, some causes of hardware problems were incorrect wiring and insufficient power supply decoupling. This insufficient power supply decoupling was solved by providing additional power supply decoupling across the appropriate pins of particular integrated circuits.

VI.1.2 MECHANICAL SYSTEM

The mechanical system consisting of the stepper motor interface to the hydraulic system, the hydraulic system, three-dimensional joystick and the three-dimensional manipulator with microelectrode holder, were individually tested. Some modifications had to be made in the design of the hydraulic system and the three-dimensional manipulator. The modifications in the hydraulic system included the inclusion of air bleeders at the master bellows and the modification of the hydraulic fluid filler system. The modification in the three-dimensional manipulator included adding a linear bearing in the "Z" plane and some modification in the microelectrode amplifier holder and the clamping system to the existing three-dimensional stand. The linear bearing had to be included in the "Z" plane to reduce any friction in this plane.

VI.2 SOFTWARE

All software was tested thoroughly during and after its development and was carefully modified until it performed as required. As software was well structured, software changes were easy to implement.

VI.3 RESULTS

The three dimensional microprocessor controlled micro-manipulator system was tested in both the joystick mode and the keyboard mode. Special care was taken in setting up the equipment to ensure that environment vibration had minimal effect on the microelectrode. Only the three dimensional hydraulic manipulator was set upon the test table with all the other associated equipment away from this table. This was done to ensure that the vibration due to stepper motors arrangement had no effect on the microelectrode. A very high magnification microscope with calibrated scale was used to view and measure the microelectrode movements in "X", "Y", and "Z" directions.

The intracellular potential was initially set to greater than cell threshold voltage (microelectrode outside the cell tissue) and the movements of the microelectrode was noticed in all three directions. Under this condition it was possible to control the microelectrode in all the directions both via joystick and keyboard. The microelectrode position was displayed as the microelectrode moved in steps of 0.5 microns.

When the intracellular potential was reduced to below the minimum cell threshold voltage, the microelectrode movements in all three directions was disabled. This state was indicated by a four beep audible/visual alarm. It was possible to force the system out of this mode via the keyboard and further control of the electrode in the "Z" direction was possible.

It was also possible to cause the microelectrode to return to the "Home" position via the keyboard.

The microscope test results are shown in Table V1.1. The relationship between the microelectrode deflection and the stepper motor steps for one channel is shown in Figure VI.1. From the results it can be seen that it is possible to control the mciroelectrode in submicrons in all three directions. The range of control of the microelectrodes was from 0 micron to 128 microns with the resolution of approximately 0.5 microns in all three directions. It was also noted that the vibration due to the stepper motors arrangement had no detectable effect on the microelectrode.

Hydraulic Fluid: Degased distilled water

Motor Steps (X,Y,Z)	Microelectrode Displacement (microns)
48	25
100	50
148	75
205	100
250	125

Table VI.1 Microscope Test Result.

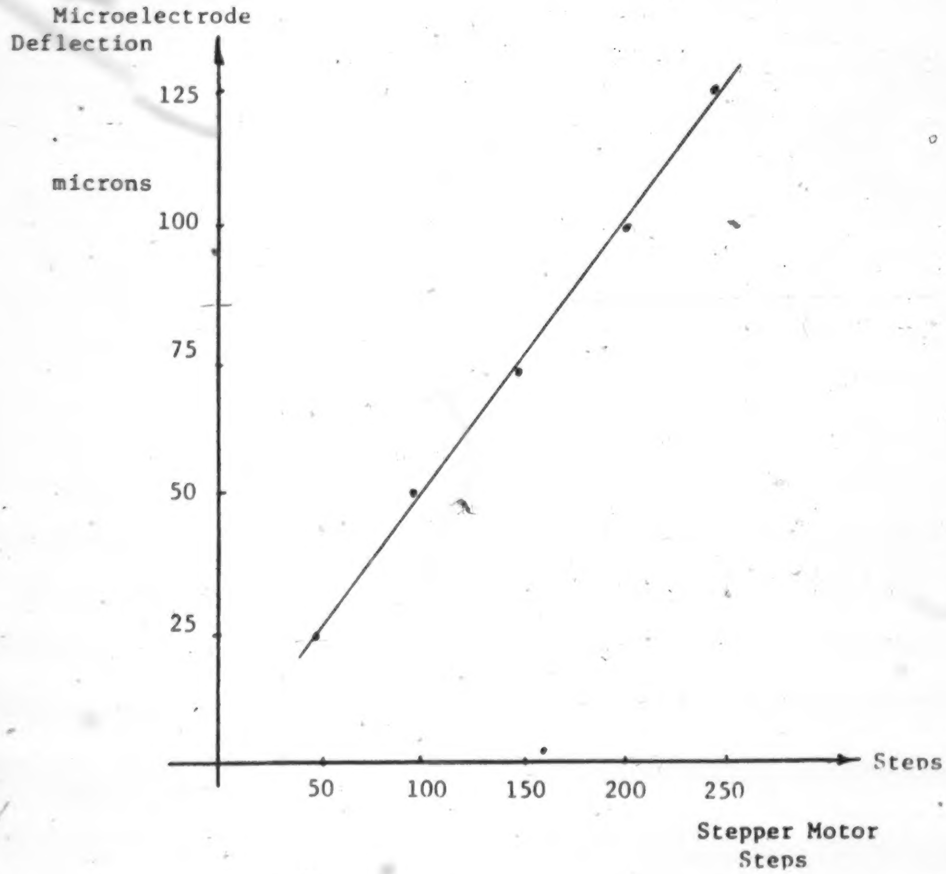


Figure VI.1 Microelectrode Deflection Vs. Stepper Motor Steps
Hydraulic Fluid : Degased Distilled Water
Microscope magnification : x 200

CHAPTER VII

CONCLUSION

The three dimensional microprocessor controlled micromanipulator system described has been constructed and the various components of the hardware and software tested. The instrument was found to perform the functions described reliably and efficiently.

The Motorola MC6809 microprocessor was chosen primarily because of the excellent software development support for this microprocessor at the University of Alberta and for the familiarity of the author with this microprocessor. In checking the system operation it has been determined that the MC6809 microprocessor is heavily utilised at its 1MHz clock frequency. However delays in response to keyboard input and displays updating are not significant. Thus the MC6809 microprocessor was a good choice in terms of processing power.

Microelectrode measurements are highly susceptible to noise because of the large electrode impedance. For this reason careful consideration was given while designing the amplifier for monitoring the intracellular potential.

The system software enables the microelectrode position to be controlled either via a three dimensional joystick or via a keyboard. The keyboard control routine enables the microelectrode position to be controlled independently in the "X", "Y" and "Z" directions. Thus in this mode it was possible to key-in any desired microelectrode position in either the "X" or "Y" or "Z" direction and the system caused the microelectrode to position itself to the keyed position. The joystick control routine enabled the continuous control of the microelectrode position via a three dimensional joystick. This mode of control enabled the fine positioning of the microelectrode in the X-Y-Z plane. It was also possible to enable the experimenter to cause the microelectrode to return to "home" position at the end of the test. The software also enabled the control parameters to be altered via the keyboard.

The stepper motor control algorithm was such that it enabled the microelectrode to follow the joystick travel in the X-Y-Z plane. The control algorithm also enabled the motors to step at varying speed such that when the number of steps to be taken were large, the motors started at a slow stepping rate of 2 steps/sec. increasing to 15 steps/sec. This algorithm ensured the microelectrode positioning itself to the desired position quickly without the stepper motor missing any step at the start or overshooting at the finish.

The mechanical system consisting of the stepper motor-interface to the hydraulic system, closed hydraulic system consisting of miniature bellows linked via polyethlyene tubes, three dimensional hydraulic controlled manipulator with microelectrode holder and the three dimensional joystick were all tested individually in the system and were found to work within the design specifications. The hydraulic link was used between the stepper motor/micrometer arrangements and the three dimensional manipulator to overcome any vibrational problems associated with moving parts. On testing the system it was found that the stepping of the stepper motors or the micrometers caused no detectable vibration of the microelectrode.

A number of problems were faced while filling the hydraulic system. These included the type of fluid being used, getting rid of the air bubbles from the hydraulic system and above all leaking bellows. Degased distilled water was used as opposed to very thin oil as a hydraulic fluid because it was less messy to work with and also it was easier to get rid of bubbles from a water filled system.

Due to the large mass of the three dimensional manipulator, it was determined that the present existing microelectrode stand to which the manipulator was attached was not stable enough. It is recommended that a better quality three dimensional stand be purchased and used to give better stability for coarse adjustment.

It is believed that this instrument will make a significant contribution to the research for which it was designed. Also the design has sufficient versatility that it could be a significant asset in physiological or biological experiment requiring micro-positioning.

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APPENDIX A

OPERATOR'S MANUAL

GENERAL FUNCTION

The function of a three-dimensional microprocessor controlled micromanipulator system is to perform the control of the position of the microelectrode position in the "X", "Y" and "Z" planes display the microelectrode position in the "X", "Y" and "Z" directions and to monitor the intracellular potential with reliability, efficiency and with as much flexibility as possible.

The three dimensional microprocessor controlled micromanipulator system can be controlled either from the front panel (via the keyboard) or by a three-dimensional joystick. The representation of the front panel control is shown in Fig. A.1. The keyboard is divided into two groups of keys; the first group is used for data entry, and the second group is used to control the three-dimensional micromanipulator system. The displays are used to indicate the microelectrode position in microns in the "X", "Y" and "Z" directions, and to indicate data entry via the keyboard. The LED displays are used to indicate different control modes namely, joystick mode, keyboard mode, standby/home mode, and the maximum penetration limit.

The three analog inputs from the joystick enter the three-dimensional microprocessor controlled micromanipulator system through the seven pin RCA plug mounted on the back panel shown in Figure A.2. The back panel also has the 24 pin connector to connect the three-stepper motors, a BNC connector to connect to the Backman Recording

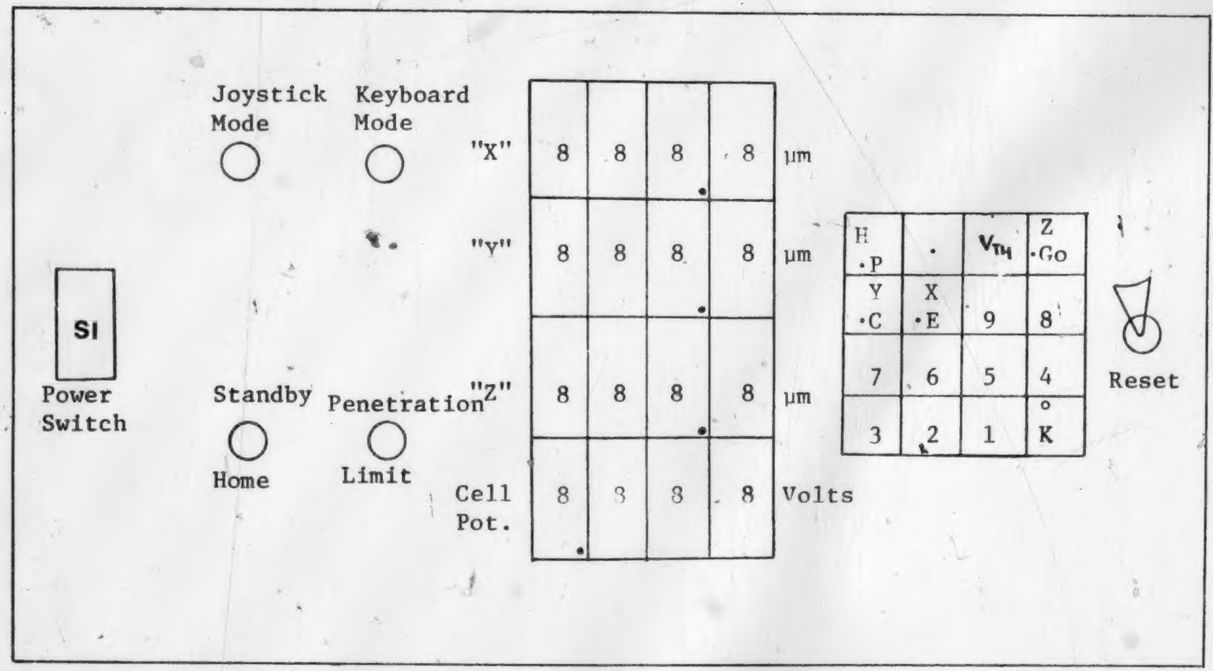

Joystick Mode
Keyboard Mode
SI
Power Switch
Standby
Home
Penetration
Limit
"X"
"Y"
"Z"
Cell Pot.
8 8 8 8
µm
µm
µm
Volts
H ·P
·
V_{TH}
Z ·Go
Y ·C
X ·E
9
8
7
6
5
4
3
2
1
° K
Reset

Figure A.1 Front Panel - Three Dimensional Microelectrode Controller

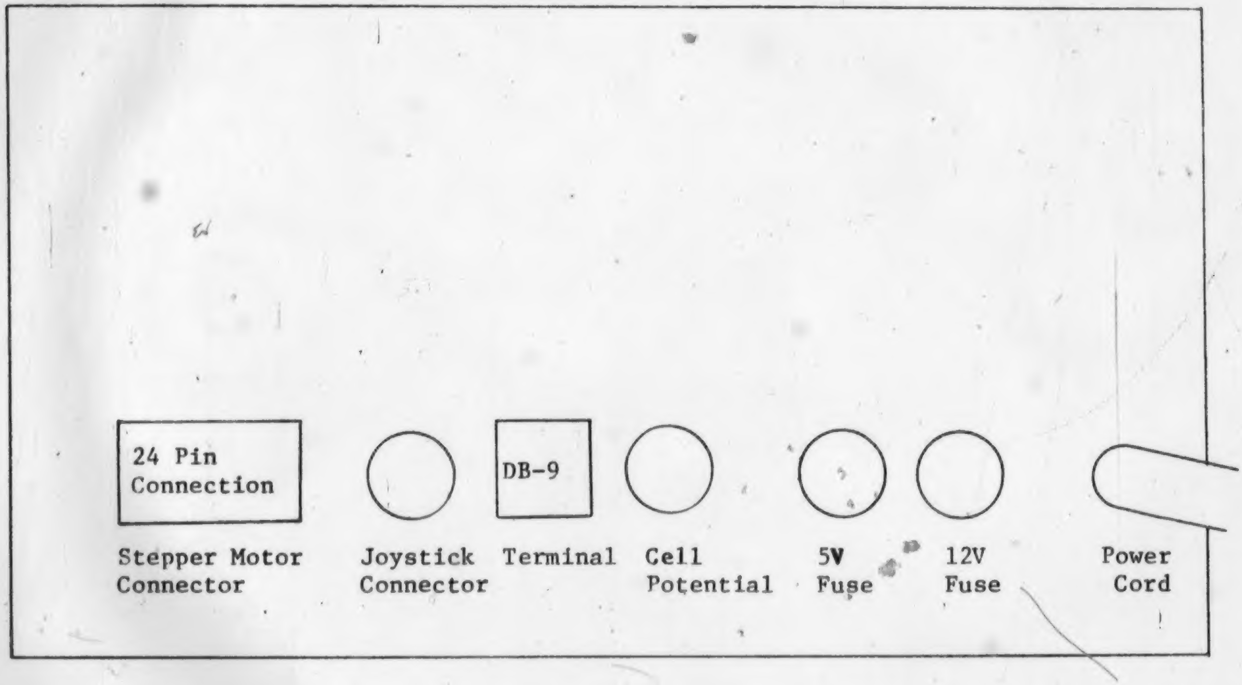

24 Pin
Connection
DB-9
Stepper Motor
Connector
Joystick
Connector
Terminal
Cell
Potential
5V
Fuse
12V
Fuse
Power
Cord

Figure A.2 Back Panel - Three Dimensional Microelectrode Controller

System for monitoring intracellular potential and a DB9 connector for system development.

START-UP

The three-dimensional microprocessor controlled micromanipulator system automatically performs the power-up reset and the system initialisation tests when the power switch S1 is switched on (indicated by power up light). The purpose of these routines are to provide the user with the highest possible confidence level that the instrument is fully functional. The end of this routine is indicated by a one second buzzer followed by flashing standby LED display.

If a failure of the power-up reset and system initialisation occurs the reset switch must be pressed, and this will allow the whole routine to be repeated.

CONTROLS

FUNCTION KEYS

The following is the description of the function keys used to operate the system.

(.) Function key.

This key is to be depressed before the function key in order to select the second function associated with a particular key. The first function is always printed on the upper half of the key. The table for the second function is printed on the lower half of the key and always begins with a dot (.).

(.C) Clear key.

This function is used to clear the data entered into the data buffer registers. It also clears the requested display.

(.E) Enter key.

This function key is used to enter data into the 8-bit data registers for further calculations, display and motor control.

(.GO) Go key.

This function is used to enable the system to return to joystick mode from standby or home mode.

(H) Home key.

This function is used to cause the three stepper motors to go into the "home" mode and return to its initial position, i.e. the position of the three stepper motors at switch "on". Once this function key is pressed the system calculates the number of steps already taken by the three stepper motors with respect to the reference position and enables the motors in the reverse direction as compared to the previous motor rotations. The "Z" stepper motor is enabled first followed by "X" and "Y" stepper motors. The system returns to the "home" mode after completing the home routine.

(V_{TH}) Minimum Threshold Voltage Key

This function key is used to enter the minimum threshold voltage into the 8-bit minimum threshold voltage regiser.

(Z) Z Stepper Motor Control.

This function key is used to select the stepper motor "Z" control routine. This routine enables the desired microelectrode displacement in microns in the "Z" direction to be entered via the keyboard. The routine also permits the data to be re-entered if an error is made in the entry of the microelecrode displacement in the "Z" direction. If the correct entry is made and the data entered the stepper motor "Z" is sequenced until the desired position is reached. The motor is sequenced in either the constant speed mode or ramp (acceleration/deceleration) mode depending on the magnitude of the displacement with respect to the present microelectrode position. The system returns to the "standby" mode after completing the routine.

(X) X Stepper Motor Control.

This function key is used to select the "X" stepper motor control routine. The routine enables the desired microelectrode displacement in microns in the "X" direction to be entered via the keyboard. If any error is made in the entry the digits can be re-entered. If the correct entry is made of the microelectrode displacement in the "X" direction the stepper motor "X" is sequenced until the desired position is reached. The motor is sequenced in either constant speed mode or ramp mode depending on the magnitude of the displacement with respect to the present microelectrode position. The system returns to the "standby mode" after completing the routine.

(Y) Y Stepper Motor Control.

This functin key is used to select the "Y" stepper motor control routine. The routine is similar to the "X" stepper motor control routine with the displacement of the microelectrode in the "Y" direction only.

(K) Keyboard mode.

This function key is used to enable the system to go into the keyboard mode. The mode is indicated by the keyboard mode LED switching on. To return into the joystick mode without any entry made, the same key (K) is pressed again.

(.P) Forced Penetration Key.

This key is used to enable the "Z" stepper motor in joystick mode once the minimum threshold voltage is reached.

(0-9) Digit.

These keys are used for data entry.

TYPICAL KEYBOARD MODE OPERATION

The following are examples of how to operate the micromanipulator system via the keyboard under typical conditions.

INDEPENDENT "X", "Y" AND "Z" MOTOR CONTROLS

These routines are used to control the three stepper motors independently to give the required displacement of the microelectrodes in either the "X", "Y" or "Z" directions.

Keystrokes	Displays	Comments
Turn power on	0 0 0.0	(i) all displays initialised
	0 0 0.0	
	0 0 0.0	
	0.0 0 0	
		(ii) one second buzzer to indicate end of set up routine
	Standby mode	(iii)indicates the system is in

	LED flashing		standby mode
(K),(X)	Keyboard mode LED on	(i)	motor "X" control routine is selected
(1)	1	(i)	"X" displacement entry with MSB first
(2)	2		
(3)	3		
(5)	5		
(.),(.C)	0 0 0.0	(i)	error in entry display/buffer cleared
(1)	1	(i)	X displacement entered again
(2)	2		
(0)	0		
(0)	0		
(.),(.E)	1 2 0.0	(i)	the "X" displacement transferred for further calculation and "X" stepper motor sequenced in the CW/CCW direction either at constant speed mode or ramp mode
	Standby LED flashing	(i)	mode end of completion of the routine the system goes into standby mode

Identical keystroke sequences are used to control stepper motors "Y" and "Z" to give displacement of the microelectrode in the "Y" and "Z" directions respectively.

HOME ROUTINE

This routine is used to enable the three stepper motors to return to its initial position at the end of the experiment. This ensures that there is no compression or expension of the bellows.

Keystroke	Display		Comments
(K),(H)	Keyboard mode LED on	(i)	system goes into the "home" routine, calculates the number of steps to be taken by each stepper motor and enables stepper motor "Z" followed by motor "X" and motor "Y". Enabling stepper motor "Z" first ensures the microelectrode comes out of the tissue, thus not causing any damage to the tissue and the microelectrode
	064.0 064.0 064.0 0.000	(ii)	the system initialises displays to the microns on "X" and "Y" and 0's for "Z" and the cell potential
	"home" LED on		goes into "home" mode at the end of the routine

THRESHOLD VOLTAGE ENTRY ROUTINE

This routine allows the minimum threshold cell voltage to be entered via the keyboard. This voltage is set to disable all the three stepper motors and allow the system to go into low power halt mode.

Any further penetration of the microelectrode into the cell can be achieved either via the keyboard or by depressing the forced penetration key and control the microelectrode via the joystick.

Threshold Voltage Entry Procedure

Keystroke	Display	Comment
(K),(V_{TH})	Keyboard LED on cell pot. 0000	Display cleared
(0)	0	Threshold voltage entry with maximum significant digit first
(2)	2	
(6)	6	
(3)	3	
(.),(.C)	cell pot. 0.000	error mode in entry. Display and buffer cleared
(0)	0	
(0)	0	
(6)	6	
(5)	5	
(.),(.E)	cell pot. 0.065	entry transferred to be converted to binary equivalent of the entry
(V_{TH})	cell pot. 0.065	The binary equivalent number stored in the 8-bit minimum threshold register. The system

returns to the address
where it was interrupted
in the main program

cell pot. intra-
cellular pot.
Joystick mode LED on

TYPICAL JOYSTICK MODE OPERATION

This mode of operation allows the operator to control the position of the microelectrode via a three-dimensional joystick. The microelectrode can be displaced in either "X", "Y" or "Z" direction in steps of 0.5 microns to a maximum of ± 64.0 microns from the initial position (no expansion or compression of the bellows). If the displacement is large, the motors stepping sequence go into a ramp speed mode whereas for small displacement (a few microns) the motors are stepped in constant speed mode.

Once the desired position in the "X"-"Y" plane has been achieved, the "Z" motor can be sequenced to cause the microelectrode to advance into the tissue. As soon as the microelectrode enters the cell (intracellular potential less than threshold voltage) the stepper motors "X", "Y" and "Z" are disabled).

The present "Z" position and the intracellular potentials are displayed, one second beeper sounded and the system goes into low power halt mode. Once in this mode the microelectrode can be advanced further either via keyboard routine or by depressing "Forced Penetration" key. This enables the microelectrode to be controlled in the "Z" direction in steps of 0.5 microns. The intracellular potential is monitored and displayed after each step of the stepper motor.

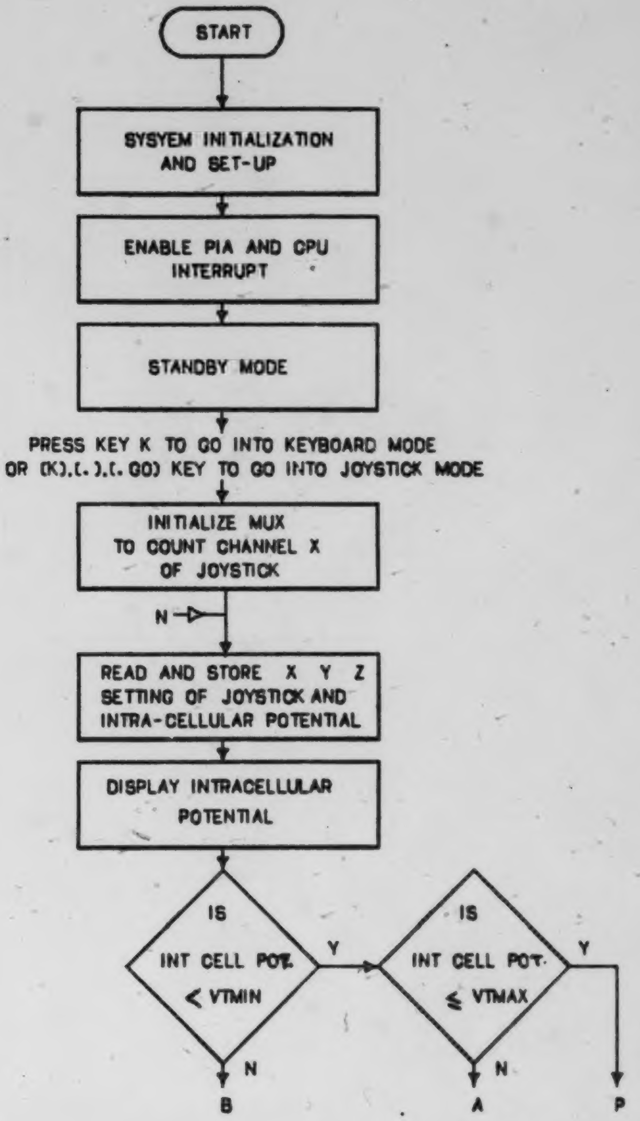
JOYSTICK CONTROL ROUTINE

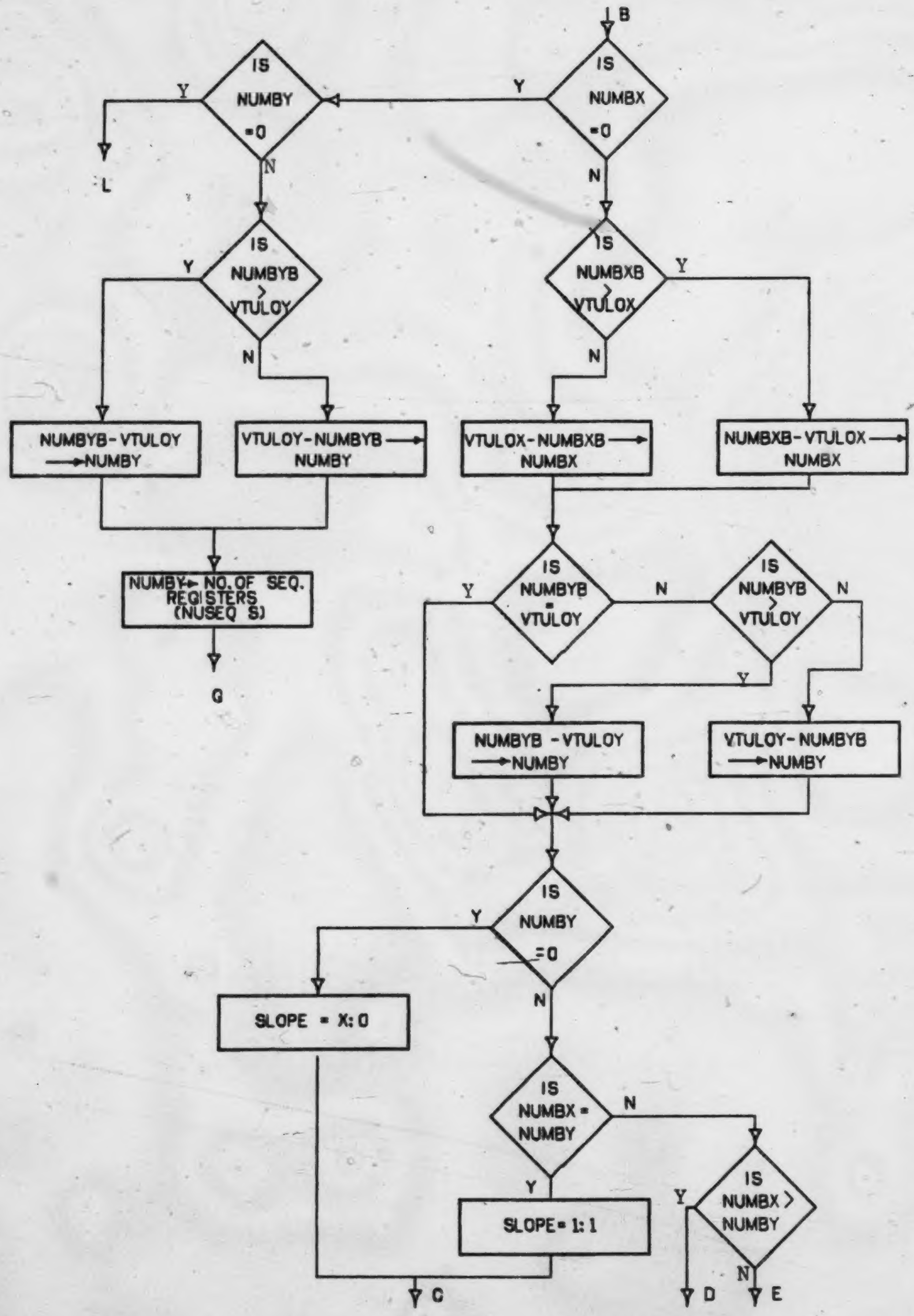
Keystroke	Display	Comments
Power on	X 000.0 Y 000.0 Z 000.0 cell pot. 0.000	(i) all displays initialised
		(ii) one sec. buzzer to indictate end of set-up routine
	standby LED flashing	(iii)system goes into standby mode
(K) (.),(.GO)	Joystick mode LED on. Actual X-Y-Z microelectrode position displayed	(i) system goes into joystick control routine
	Maximum penetration LED flashing and audible alarm sounded	(i) intracellular potential less than cell threshold voltage.System in "Halt" mode
(K) (.),(.P)	Actual "X-Y-Z" microelectrode position displayed	(i) system enables further control of microelectrode position in "Z" direction

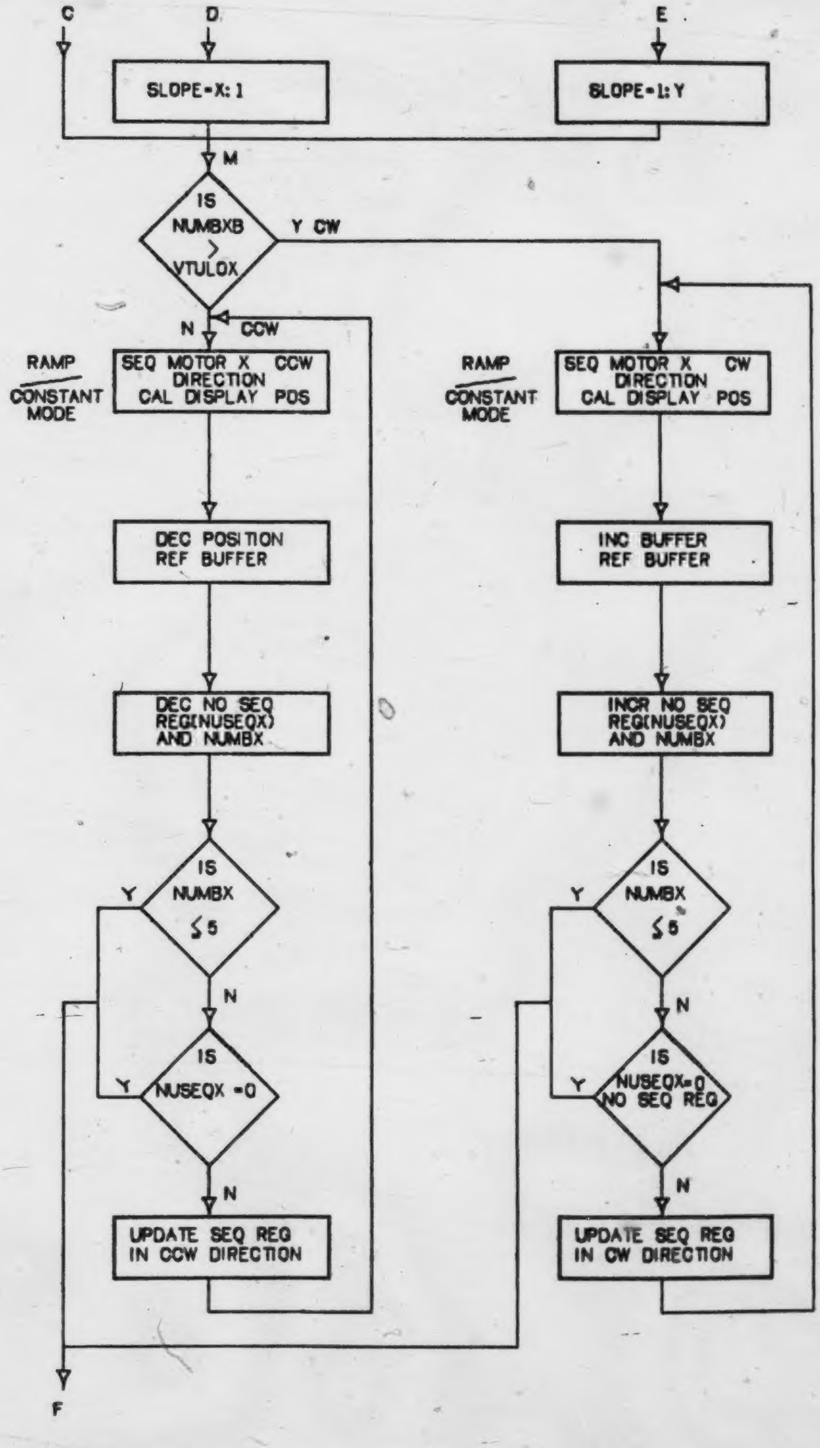
At the end of the experiment the microelectrode must be returned to its initial position. Refer to keyboard mode operation of "home" routine control.

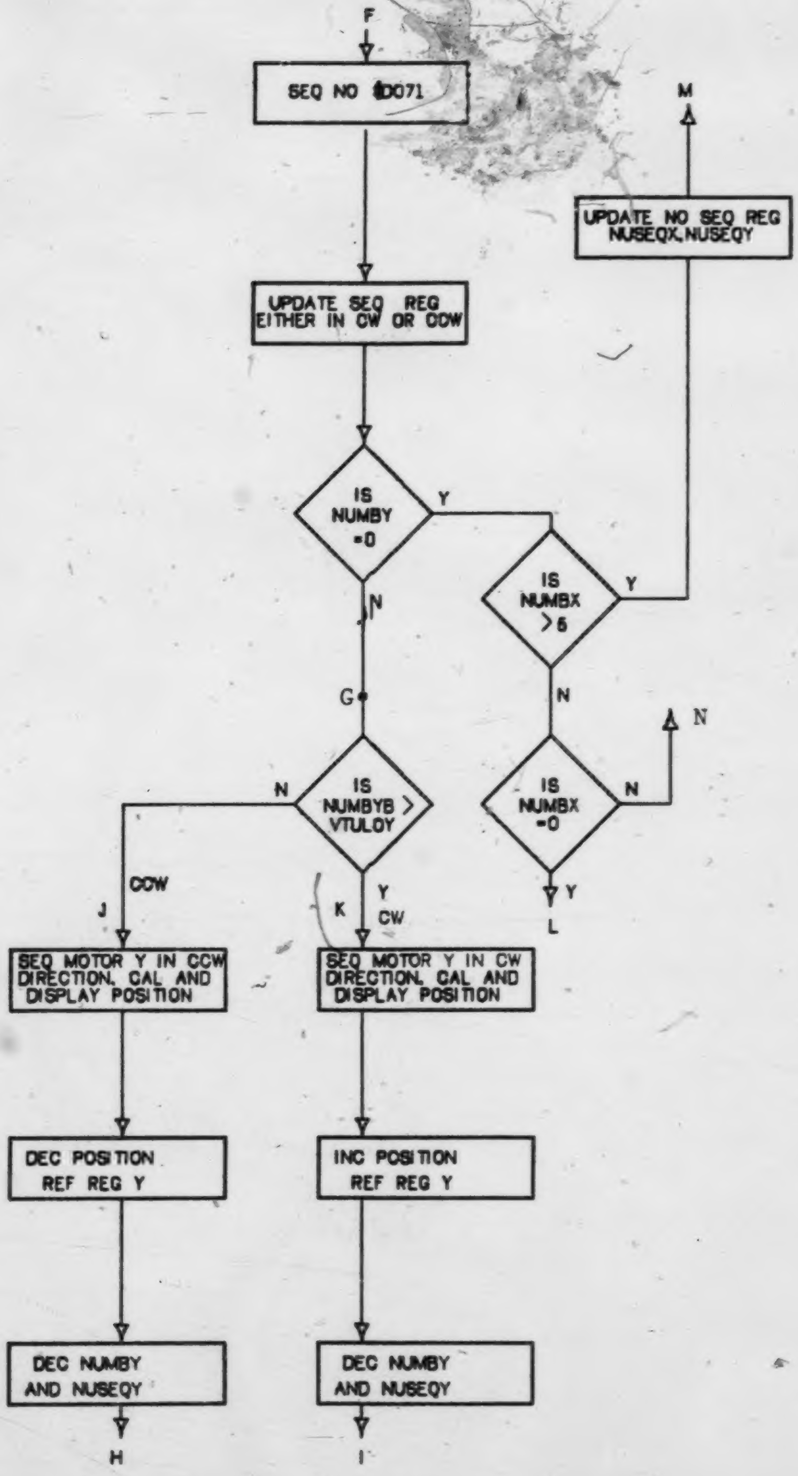
APPENDIX B

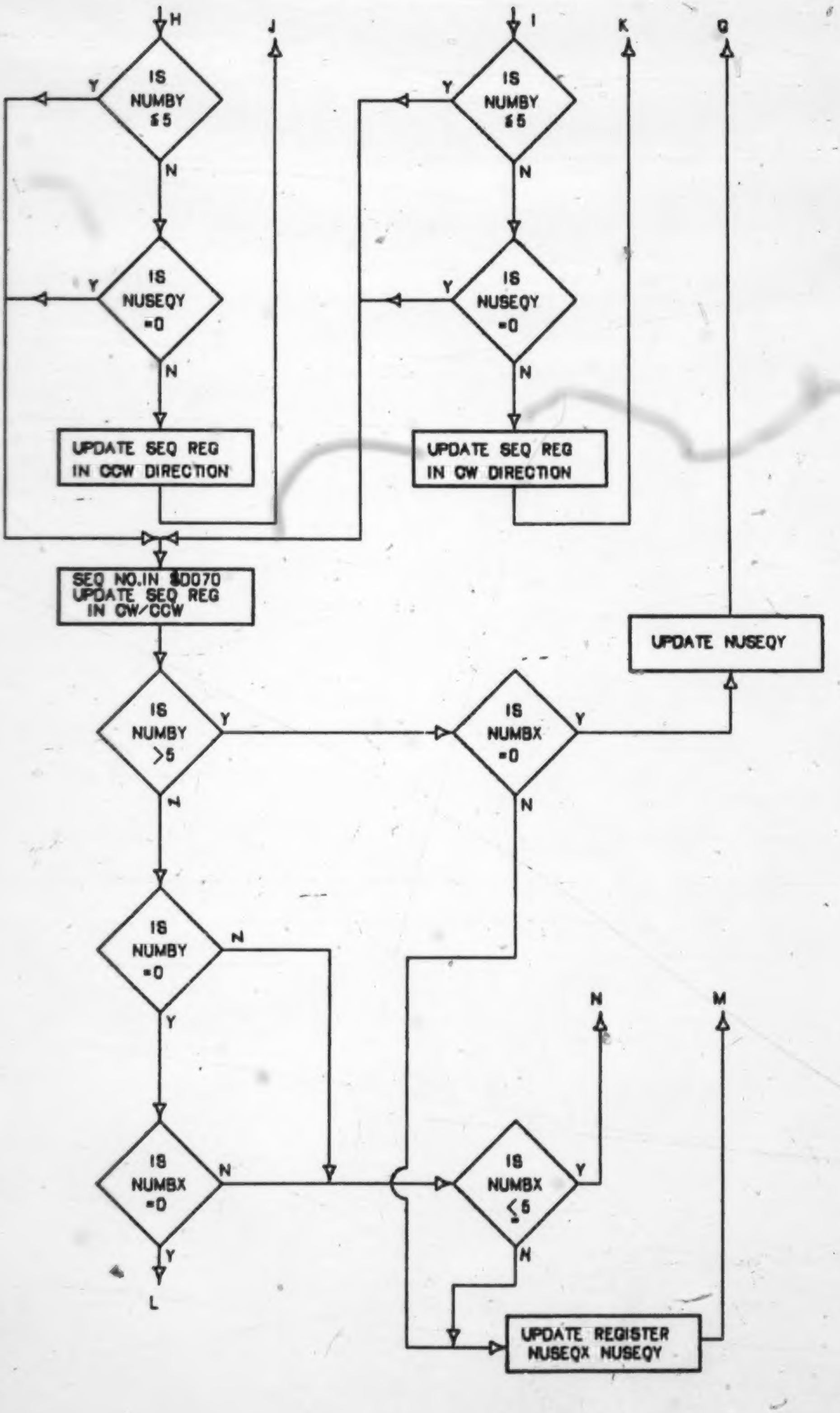
This appendix describes the Main Program and the Interrupt Routine flow charts and the Program listing. The Main Program object code resides in EPROM 1 and the Interrupt Routine object code resides in EPROM 2.

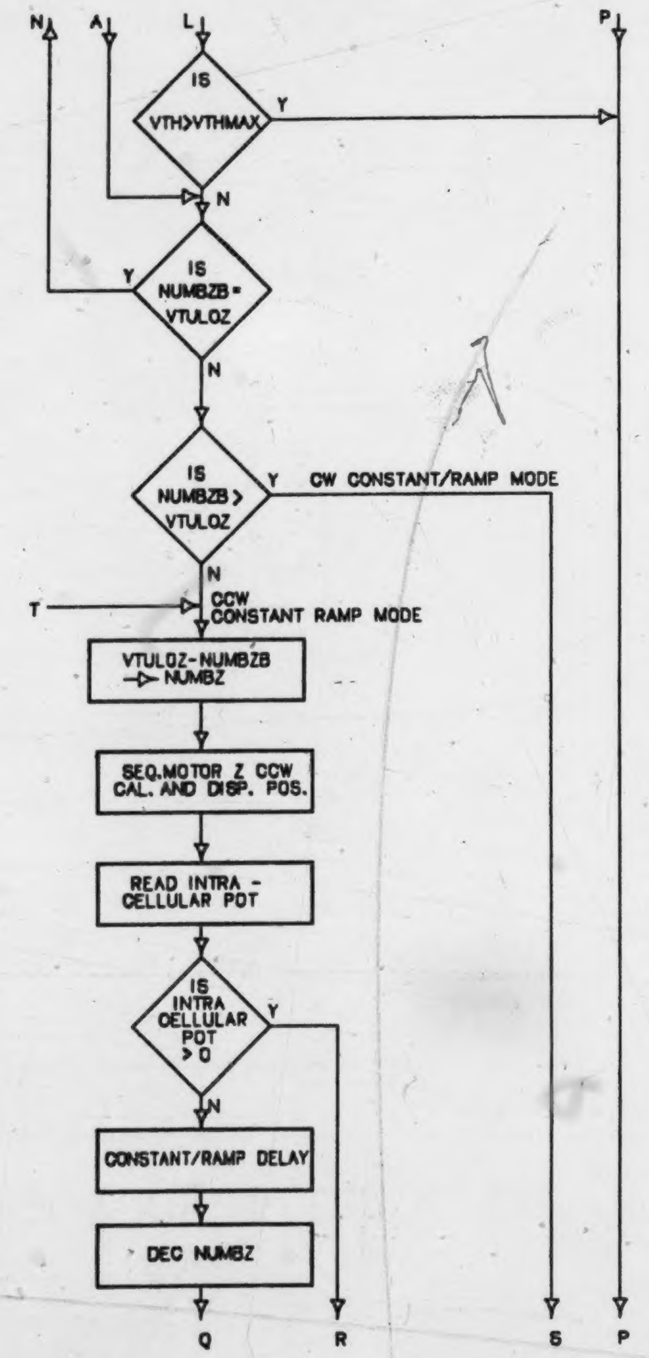

START
SYSYEM INITIALIZATION AND SET-UP
ENABLE PIA AND CPU INTERRUPT
STANDBY MODE
PRESS KEY K TO GO INTO KEYBOARD MODE
OR (K).(.).(. GO) KEY TO GO INTO JOYSTICK MODE
INITIALIZE MUX TO COUNT CHANNEL X OF JOYSTICK
N
READ AND STORE X Y Z SETTING OF JOYSTICK AND INTRA-CELLULAR POTENTIAL
DISPLAY INTRACELLULAR POTENTIAL
IS INT CELL POT. < VTMIN
Y
N
B
IS INT CELL POT. ≤ VTMAX
Y
N
A
P

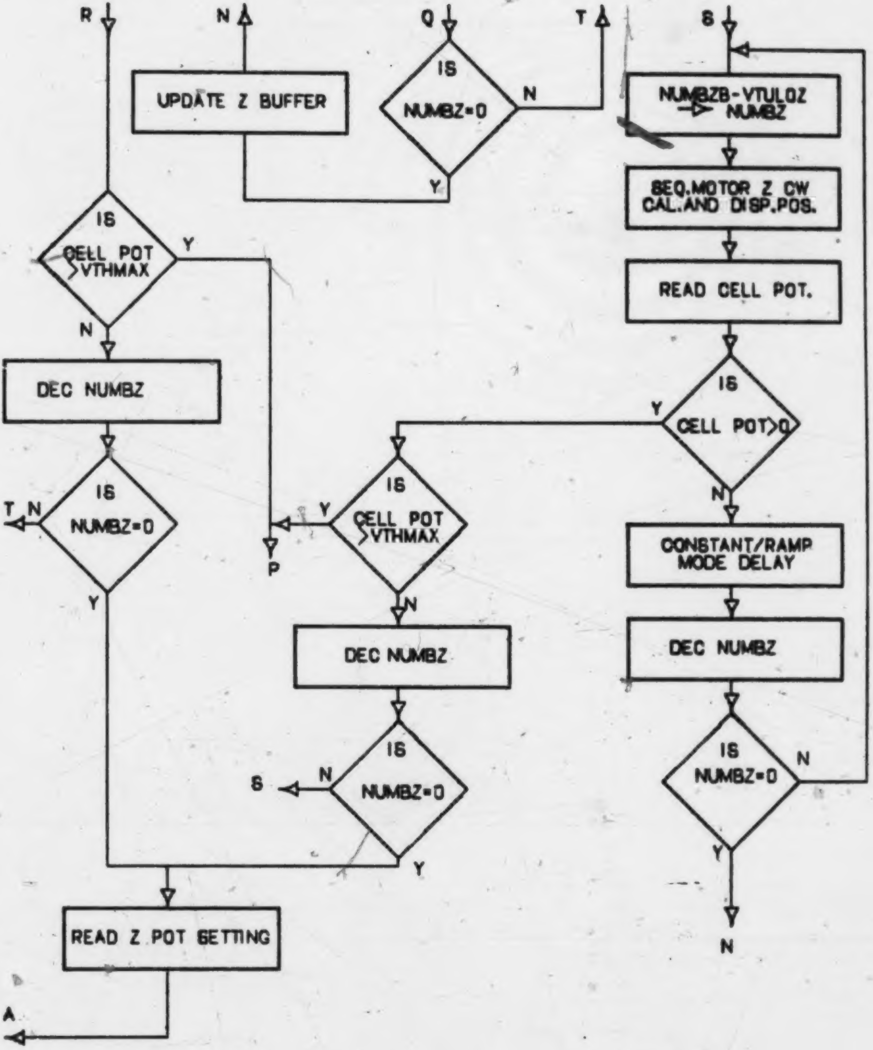

B
IS NUMBX =0
Y
N
IS NUMBY =0
Y
L
N
IS NUMBYB > VTULOY
Y
N
NUMBYB - VTULOY ⟶ NUMBY
VTULOY - NUMBYB ⟶ NUMBY
NUMBY ← NO. OF SEQ. REGISTERS (NUSEQ S)
G
IS NUMBXB > VTULOX
Y
N
VTULOX - NUMBXB ⟶ NUMBX
NUMBXB - VTULOX ⟶ NUMBX
IS NUMBYB = VTULOY
Y
N
IS NUMBYB > VTULOY
Y
N
NUMBYB - VTULOY ⟶ NUMBY
VTULOY - NUMBYB ⟶ NUMBY
IS NUMBY =0
Y
N
SLOPE = X: 0
IS NUMBX = NUMBY
Y
N
SLOPE = 1: 1
IS NUMBX > NUMBY
Y
N
C
D
E

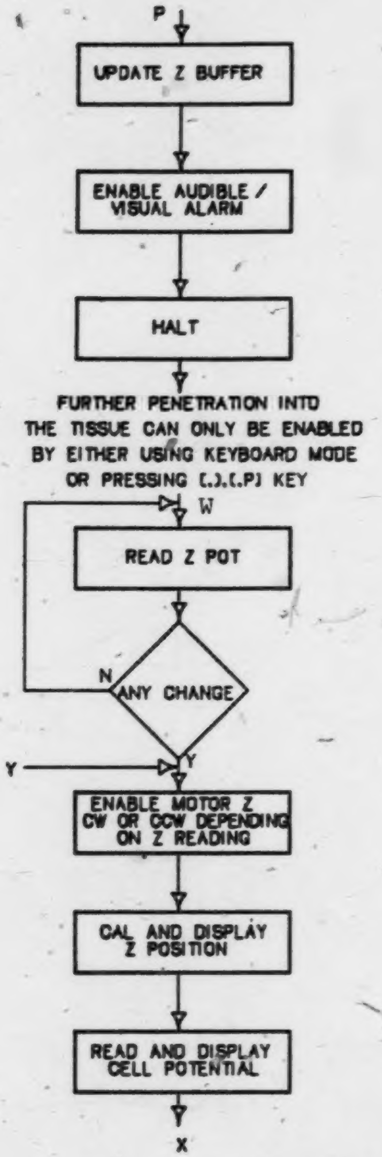

C
D
E
SLOPE=X:1
SLOPE=1:Y
M
IS NUMBXB > VTULOX
Y CW
N
CCW
RAMP
CONSTANT MODE
SEQ MOTOR X CCW DIRECTION CAL DISPLAY POS
SEQ MOTOR X CW DIRECTION CAL DISPLAY POS
DEC POSITION REF BUFFER
INC BUFFER REF BUFFER
DEC NO SEQ REG(NUSEQX) AND NUMBX
INCR NO SEQ REG(NUSEQX) AND NUMBX
IS NUMBX ≤5
Y
N
IS NUSEQX =0
IS NUSEQX=0 NO SEQ REG
UPDATE SEQ REG IN CCW DIRECTION
UPDATE SEQ REG IN CW DIRECTION
F


F
SEQ NO $0071
M
UPDATE NO SEQ REG NUSEQX,NUSEQY
UPDATE SEQ REG EITHER IN CW OR CCW
IS NUMBY =0
Y
N
IS NUMBX >5
Y
N
G
IS NUMBYB > VTULOY
N
IS NUMBX =0
N
N
Y
L
CCW
J
Y
K
CW
SEQ MOTOR Y IN CCW DIRECTION, CAL AND DISPLAY POSITION
SEQ MOTOR Y IN CW DIRECTION, CAL AND DISPLAY POSITION
DEC POSITION REF REG Y
INC POSITION REF REG Y
DEC NUMBY AND NUSEQY
DEC NUMBY AND NUSEQY
H
I


H
J
I
K
G
IS NUMBY ≤5
Y
N
IS NUSEQY =0
Y
N
UPDATE SEQ REG IN CCW DIRECTION
IS NUMBY ≤5
Y
N
IS NUSEQY =0
Y
N
UPDATE SEQ REG IN CW DIRECTION
SEQ NO.IN $0070 UPDATE SEQ REG IN CW/CCW
UPDATE NUSEQY
IS NUMBY >5
Y
N
IS NUMBX =0
Y
N
IS NUMBY =0
N
Y
N
M
IS NUMBX =0
N
Y
L
IS NUMBX ≤5
Y
N
UPDATE REGISTER NUSEQX NUSEQY


N
A
L
P
IS
VTH>VTHMAX
Y
N
IS
NUMBZB =
VTULOZ
Y
N
IS
NUMBZB >
VTULOZ
Y
CW CONSTANT/RAMP MODE
N
T
CCW
CONSTANT RAMP MODE
VTULOZ-NUMBZB
→ NUMBZ
SEQ.MOTOR Z CCW
CAL. AND DISP. POS.
READ INTRA -
CELLULAR POT
IS
INTRA
CELLULAR
POT
> 0
Y
N
CONSTANT/RAMP DELAY
DEC NUMBZ
Q
R
S
P


R
N
Q
T
S
UPDATE Z BUFFER
IS
NUMBZ=0
N
Y
NUMBZB-VTULOZ → NUMBZ
SEQ.MOTOR Z CW
CAL.AND DISP.POS.
READ CELL POT.
IS
CELL POT >VTHMAX
Y
N
DEC NUMBZ
IS
CELL POT>0
Y
N
IS
NUMBZ=0
T
N
Y
IS
CELL POT >VTHMAX
Y
P
N
CONSTANT/RAMP MODE DELAY
DEC NUMBZ
DEC NUMBZ
IS
NUMBZ=0
S
N
Y
IS
NUMBZ=0
N
Y
N
READ Z POT SETTING
A


P
UPDATE Z BUFFER
ENABLE AUDIBLE / VISUAL ALARM
HALT
FURTHER PENETRATION INTO THE TISSUE CAN ONLY BE ENABLED BY EITHER USING KEYBOARD MODE OR PRESSING [.],[.P] KEY
W
READ Z POT
N
ANY CHANGE
Y
Y
ENABLE MOTOR Z CW OR CCW DEPENDING ON Z READING
CAL AND DISPLAY Z POSITION
READ AND DISPLAY CELL POTENTIAL
X

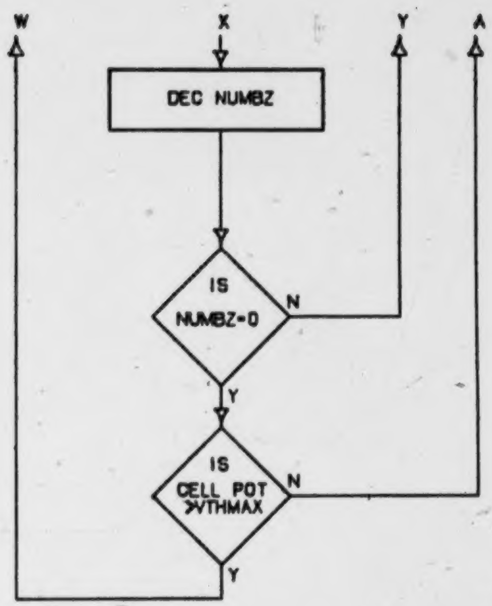

W
X
Y
A
DEC NUMBZ
IS
NUMBZ=0
N
Y
IS
CELL POT
>VTHMAX
N
Y

Figure B.1 Main Program Flow Chart

MAIN PROGRAM

```
OBJECT CODE      SOURCE STATEMENT

          8001  PIA1CA  EQU  $8001
          8000  PIA1DA  EQU  $8000
          8000  PA1DDA  EQU  $8000
          8003  PIA1CB  EQU  $8003
          8002  PIA1DB  EQU  $8002
          8002  PA1DDB  EQU  $8002
          9001  PIA2CA  EQU  $9001
          9000  PIA2DA  EQU  $9000
          9000  PA2DDA  EQU  $9000
          9003  PIA2CB  EQU  $9003
          9002  PIA2DB  EQU  $9002
          9002  PA2DDB  EQU  $9002
          D000  DIGT1   EQU  $D000     X DISPLAY REGISTERS
          D001  DIGT2   EQU  $D001
          D002  DIGT3   EQU  $D002
          D003  DIGT4   EQU  $D003
          D004  DIGT5   EQU  $D004     Y DISPLAY REGISTERS
          D005  DIGT6   EQU  $D005
          D006  DIGT7   EQU  $D006
          D007  DIGT8   EQU  $D007
          D008  DIGT9   EQU  $D008     Z DISPLAY REGISTERS
          D009  DIGT0A  EQU  $D009
          D00A  DIGT0B  EQU  $D00A
          D00B  DIGT0C  EQU  $D00B
          D00C  DIGT0D  EQU  $D00C     THRESHOLD VOLTAGE STORAGE REGISTERS
          D00D  DIGT0E  EQU  $D00D
          D00E  DIGT0F  EQU  $D00E
          D00F  DIGT20  EQU  $D00F
```

```
D010  BUFF1   EQU  $D010      X DISPLAY BUFFER REGISTERS
D011  BUFF2   EQU  $D011
D012  BUFF3   EQU  $D012
D013  BUFF4   EQU  $D013
D014  BUFF5   EQU  $D014      Y DISPLAY BUFFER REGISTERS
D015  BUFF6   EQU  $D015
D016  BUFF7   EQU  $D016
D017  BUFF8   EQU  $D017
D018  BUFF9   EQU  $D018      Z DISPLAY BUFFER REGISTERS
D019  BUFF0A  EQU  $D019
D01A  BUFF0B  EQU  $D01A
D01B  BUFF0C  EQU  $D01B
D01C  BUFF0D  EQU  $D01C      THRESHOLD VOLT. DISPLAY BUFF. REG.
D01D  BUFF0E  EQU  $D01D
D01E  BUFF0F  EQU  $D01E
D01F  BUFF20  EQU  $D01F
C000  DISP1   EQU  $C000      DISPLAY 1 (X Y REGISTER)
C008  DISP2   EQU  $C008      DISPLAY 2 (Z VTH REGISTER)
D020  NUMBXB  EQU  $D020      JOYSTICK SETTING X BUFFER REG.
D021  NUMBYB  EQU  $D021      JOYSTICK SETTING Y BUFFER REG.
D022  NUMBZB  EQU  $D022      JOYSTICK SETTING Z BUFFER REGISTER
D023  NUMBVT  EQU  $D023      THRESHOLD VOLTAGE BUFFER REGISTER
D026  NUMBX   EQU  $D026      STEPS FOR X STEPPING MOTOR REGISTER
D027  NUMBY   EQU  $D027      STEPS FOR Y STEPPING MOTOR REGISTER
D028  NUMBZ   EQU  $D028      STEPS FOR Z STEPPING MOTOR REGISTER
D029  NUMBZ0  EQU  $D029
D02A  MULTX   EQU  $D02A      DISPLAY REFERENCE X REGISTER
D02B  MULTY   EQU  $D02B      DISPLAY REFERENCE Y REGISTER
D02C  MULTZ   EQU  $D02C      DISPLAY REFERENCE Z REGISTER
D02D  MULTPD  EQU  $D02D      MULTIPLICAND REGISTER
D02E  VTHMAX  EQU  $D02E      MAXIMUM VTH REGISTER
D030  VTHMIN  EQU  $D030      MINIMUN VTH REGISTER
D032  VTUL0X  EQU  $D032      MOTOR DIRECTION REF. X REGISTER
D033  VTUL0Y  EQU  $D033      MOTOR DIRECTION REF. Y REGISTER
```

```
D034  VTUL0Z  EQU  $D034      MOTOR DIRECTION REF. Z REGISTER
D035  ANSHEX  EQU  $D035      16 BIT REG. TO STORE HEX. ANSWER
D037  ANSDEC  EQU  $D037      16 BIT REG. TO STORE DEC. ANSWER
D03D  MULTZ0  EQU  $D03D
D03F  COUNT   EQU  $D03F
D040  SEQXZ   EQU  $D040      STEPPING MOTORS X,Z STEP.SEQ. REG.
D044  SEQY    EQU  $D044      STEPPING MOTOR Y STEPPING SEQ. REG.
D048  ANSCON  EQU  $D048
D050  COUNTR  EQU  $D050
D051  NUMBER  EQU  $D051
D052  COUNTX  EQU  $D052
D067  NUMY    EQU  $D067      SEQUENCE Y COUNTER REGISTER
D069  NUMX    EQU  $D069      SEQUENCE X COUNTER REGISTER
D065  NUMZ    EQU  $D065      SEQUENCE Z COUNTER REGISTER
D084  COUNTA  EQU  $D084
D085  COUNTB  EQU  $D085
D074  MLRTIO  EQU  $D074      8 BIT RATIO DIVIDENT REG.
D075  NUSEQX  EQU  $D075      SEQ. REPITION REGISTER
D076  NUSEQY  EQU  $D076
D081  NUSEX   EQU  $D081
D082  NUSEY   EQU  $D082
D078  MURTIO  EQU  $D078      16 BIT RATIO REGISTER
D080  CONT    EQU  $D080
D092  STPZ    EQU  $D092
F800  RESET   EQU  $F800      RESET VECTOR
F000  INTRPT  EQU  $F000
      *
      *
      *********************************************************
      * THREE  DIMENSIONAL  MICROPROCESSOR CONTROLLED  TISSUE *
      * PERFUSION SYSTEM  FOR MICROELECTRODE  MEASUREMENT     *
      *       SYSTEM  INITIALISATION                          *
      *********************************************************
      *
```

```
                   *
F800                      ORG RESET
F800 10CE DFFF            LDS #$DFFF          STACK POINTER TO HIGHEST MEMORY
F804 CE   DCFF            LDU #$DCFF          USER STACK POINTER AT DAFF
                   *
                   *
                   *********************************************************
                   *                                                       *
                   *  PIA1 & PIA2 INITIALISATION.                          *
                   *          PIA1   PORT1 =  KEYBOARD P0A P03             *
                   *                 PORTB = STEPPER MOTOR X PB0 - PB3     *
                   *                         STEPPER MOTOR Y PB4 - PB7     *
                   *          PIA2 - PORTA = ADC PA0 - PA7                 *
                   *                 PORTB = STEPPER MOTOR Z PB0 - PB3     *
                   *                         CLOCK PB5                     *
                   *                         DISPLAY1 PB7                  *
                   *                         DISPLAY2 PB6                  *
                   *********************************************************
                   *
                   *
F807 7F   8001            CLR PIA1CA
F80A 7F   8003            CLR PIA1CB         ADDRESS DATA DIRECTION REGISTERS
F80D 7F   9001            CLR PIA2CA
F810 7F   9003            CLR PIA2CB
F813 7F   9000            CLR PA2DDA
F816 86   FF              LDA #$FF
F818 B7   8002            STA PA1DDB         MAKE PORT B'S OUTPUT
F81B B7   9002            STA PA2DDB
F81E 86   F0              LDA #$F0
F820 B7   8000            STA PA1DDA         MAKE PORT A PB0-3 I/P  PB4-7 O/P
F823 86   07              LDA #%00000111     ENABLE KEYBOARD INTRRUPT
F825 B7   8001            STA PIA1CA         & ADDRESS DATA REG.  PIA1
F828 86   04              LDA #%00000100
F82A B7   8003            STA PIA1CB         ADDRESS DATA REG.
```

```
F82D B7   9001          STA PIA2CA
F830 B7   9003          STA PIA2CB
                   *
                   *
                   *****************************************************
                   *                                                   *
                   *      LOAD MAXIMUM AND MINIMUM VALUES OF VTH.      *
                   *                                                   *
                   *****************************************************
                   *
                   *
F833 7F   D030          CLR VTHMIN          VTHMIN = 0MV
F836 86   32            LDA #50
F838 B7   D02E          STA VTHMAX          VTHMAX = 50MV
                   *
                   *
                   *****************************************************
                   *                                                   *
                   *     MOTOR SEQUENCE INITIALISATION                 *
                   *                                                   *
                   *       STEPPING SEQUENCE                           *
                   *      Q4    Q3    Q2    Q1                         *
                   *                                                   *
                   *      1     0     1     0    = $0A                 *
                   *      1     0     0     1    = $09                 *
                   *      0     1     0     1    = $05                 *
                   *      0     1     1     0    = $06                 *
                   *                                                   *
                   *      MOTOR X STEPPING SEQUENCE                    *
                   *       $0A $09 $05 $06                             *
                   *      MOTOR Y STEPPING SEQUENCE                    *
                   *       $A0 $90 $50 $60                             *
                   *      MOTOR Z STEPPING SEQUENCE                    *
                   *        $0A $09 $05 $06                            *
```

```
                    *                                                   *
                    *    SEQXZ  AND SEQY CONTAIT THE VALUES NEEDED      *
                    *    TO STEP THE MOTOR X ,  Y , Z ,                 *
                    *    IN CLOCKWISE AND COUNTER CLOCKWISE DIRECTION   *
                    *****************************************************
                    *
                    *
F83B 8E   090A            LDX #$090A            ********        ********
F83E BF   D042            STX SEQXZ+2           * 0A   *        * A0   *
F841 8E   0605            LDX #$0605            ********        ********
F844 BF   D040            STX SEQXZ             * 09   *        * 90   *
F847 8E   90A0            LDX #$90A0            ********        ********
F84A BF   D046            STX SEQY+2            * 05   *        * 50   *
F84D 8E   6050            LDX #$6050            ********        ********
F850 BF   D044            STX SEQY              * 06   *        * 60   *
                    *                     SEQXZ ********  SEQY  ********
                    *
F853 7F   D070            CLR $D070
F856 7F   D071            CLR $D071
F859 7F   D072            CLR $D072
                    *
                    *
                    ******************************************************
                    *                                                    *
                    *      MULTIPLIER AND MULTIPLICAND INITIALISATION    *
                    * REFERENCE VALUE TO DETERMINE THE NUMBER            *
                    * OF STEPS TAKEN IN EITHER + OR - DIRECTION          *
                    * TO CALC. DISPLACEMENT FROM REF.                    *
                    * AND DISPLAY REGISTERS X , Y , Z , VTH              *
                    * INITIALISATION                                     *
                    *                                                    *
                    ******************************************************
                    *
                    *
```

```
F85C 86   80                LDA #%10000000    INITIALISE DESPLAY REF. REG.
F85E B7   D02A              STA MULTX         X Y Z WITH     64.0 MICRONS
F861 B7   D02B              STA MULTY
F864 B7   D02C              STA MULTZ
F867 B7   D032              STA VTUL0X        INITIALISE DIR. OF ROTATION
F86A B7   D033              STA VTUL0Y        REGISTERS X , Y , Z WITH $80
F86D B7   D034              STA VTUL0Z
F870 86   05                LDA #5            SET MULT. FACTOR TO 0.5 MICRONS
F872 B7   D02D              STA MULTPD
                   *
F875 8E   0003              LDX #3            SET SEQUENCE COUNTER REGS. TO 3
F878 BF   D065              STX NUMZ          THIS WILL ENSURE EITHER $06 (X,Z)
F87B BF   D069              STX NUMX          OR $60 (Y) TO BE LOADED INTO PIA.
F87E BF   D067              STX NUMY
                   *
                   *
                   ******************************************************
                   *                                                    *
                   *       DISPLAY INITIALISATION                       *
                   *          SET ALL DIGITS TO ZERO                    *
                   *                                                    *
                   ******************************************************
                   *
                   *
F881 4F                     CLRA
F882 C6   20                LDB #$20
F884 8E   0000              LDX #0
F887 A7   89 D000  CONTDP STA DIGT1,X
F88B 30   01                LEAX 1,X
F88D 5A                     DECB
F88E 26   F7                BNE CONTDP
F890 BD   F6F5              JSR DISPL1          DISPLAY X AND Y
F893 BD   F70A              JSR DISPL2          DISPLAY Z AND VTH
                   *
                   *
                   *****************************************************
                   *                                                   *
                   *  SEND 1 SEC BEEP AT THE END OF INITIALISATION     *
                   *   AND ENABLE CPU INTRUPT                          *
                   *                                                   *
                   *****************************************************
                   *
                   *
F896 86   0A              LDA #$0A
F898 B7   9002            STA PIA2DB
F89B BD   F6CC            JSR DELY4
F89E C6   FF              LDB #255
F8A0 86   1A       BUZZ   LDA #%00011010      TAKE TO 1 TO SOUND BEEP
F8A2 B7   9002            STA PIA2DB
F8A5 BD   F6CC            JSR DELY4
F8A8 86   0A              LDA #$0A            TAKE TO ZERO TO SWITCH
F8AA B7   9002            STA PIA2DB          OFF BEEP
F8AD BD   F6CC            JSR DELY4
F8B0 5A                   DECB
F8B1 26   ED              BNE BUZZ
                   *
                   *
F8B3 1C   EF              ANDCC #%11101111    ENABLE CPU INTERRUPT
                   *
                   *
F8B5 20   39              BRA KTEST           END OF INITIALISATION
                   *                          GO TO STAND-BY MODE
                   *
                   *******************************************************
                   *                                                     *
                   *   SYSTEM RETURNS FROM KEYBOARD MODE AFTER REACHING  *
                   *   "home" POSITION . THE DISPLAYS ARE SET TO         *
                   *   64.0 MICRONS (X & Y) AND ZERO ON Z & VTH .        *
                   *   THE SYSTEM GOES INTO STANDBY MODE INDICATING      *
                   *   HOME POSITION .                                   *
                   *   TO GET BACK INTO JOYSTICK MODE THE OPERATOR       *
                   *   HAS TO GO INTO KEYBOARD MODE AND DEPRESS  "."    *
                   *   KEY FOLLOWED BY "GO" KEY . TO GET INTO  KEYBOARD *
                   *   MODE THE "K" KEY ON THE KEYBOARD HAS TO BE        *
                   *   DEPRESSED .                                       *
                   *                                                     *
                   *   IT IS IMPORTANT THAT THE SYSTEM IS TAKEN TO       *
                   *   "home" POSITION BEFORE SWITCH OFF . FAILURE TO    *
                   *   DO THIS CAN RESULT IN THE MASTER BELLOWS          *
                   *   BEING  RAPTURED .                                 *
                   *                                                     *
                   *******************************************************
                   *
                   *
F8B7 8E   0280     RTNINT LDX #640
F8BA BF   D035            STX ANSHEX          SET X DISPLAY TO 64.0 MICRONS
F8BD 108E 0000            LDY #0
F8C1 BD   FDFF            JSR HEXDEC
F8C4 BD   F6F5            JSR DISPL1
F8C7 8E   0280            LDX #640
F8CA BF   D035            STX ANSHEX          SET Y DISPLAY TO 64.0 MICRONS
F8CD 108E 0004            LDY #4
F8D1 BD   FDFF            JSR  HEXDEC
F8D4 BD   F6F5            JSR DISPL1
F8D7 4F                   CLRA                SET Z AND VTH DISPLAYS TO ZERO
F8D8 C6   08              LDB #8
F8DA 8E   0000            LDX #0
F8DD A7   89 D008  CONDSP STA DIGT9,X
F8E1 30   01              LEAX 1,X
F8E3 5A                   DECB
F8E4 26   F7              BNE CONDSP
F8E6 BD   F70A            JSR DISPL2
```

```
F8E9 86   B0              LDA #%10110000
F8EB B7   8000            STA PIA1DA
F8EE 20   FE       HTEST  BRA HTEST         WAIT IN LOW POWER "home" MODE
                   *
                   *
                   *****************************************************
                   *                                                   *
                   *   STAND - BY MODE . SYSTEM ALWAYS GOES TO         *
                   *   STAND-BY MODE ON RETURNING FROM KEYBOARD        *
                   *   MODE . THIS MODE IS INDICATED BY FLASHING       *
                   *   LED  DISPLAY ON FRONT PANEL .  TO GET OUT       *
                   *   OF THE STAND-BY MODE THE OPERATOR HAS TO GO     *
                   *   INTO KEYBOARD MODE AND DEPRESS  "." KEY         *
                   *   FOLLOWED BY "GO" KEY . THIS WILL TAKE THE       *
                   *   SYSTEM INTO JOYSTICK MODE FOR FINE CONTROL.     *
                   *                                                   *
                   *****************************************************
                   *
                   *
F8F0 86   90       KTEST  LDA #%10010000
F8F2 B7   8000            STA PIA1DA        "FLASH" STAND-BY LED
F8F5 BD   F6D5            JSR DELY2
F8F8 86   80              LDA #%10000000
F8FA B7   8000            STA PIA1DA
F8FD BD   F6D5            JSR DELY2
F900 20   EE              BRA KTEST
                   *
                   *
                   ****************************************************
                   *                                                  *
                   *  INITIALISE  COUNTER. ALL OUTPUTS EQUAL TO ZERO. *
                   *  THIS ENSURES THAT THE ANALOG MULTIPLEXER        *
                   *  OUTPUT IS CONNECTED TO CHANNEL X  (JOYSTICK     *
                   *  X POTENTIOMETER) .                              *
                   *                                                  *
                   ****************************************************
                   *
                   *
F902 86   C0              LDA #%11000000     CLEAR ALL COUNTER O/P
F904 B7   8000            STA PIA1DA         TO CONNECT CHANNEL X
F907 86   40              LDA #%01000000
F909 B7   8000            STA PIA1DA
F90C 86   C0              LDA #%11000000
F90E B7   8000            STA PIA1DA
F911 BD   F6D5            JSR DELY2
                   *
                   *
                   *****************************************************
                   *                                                   *
                   *   READ JOYSTICK INPUT DATA (X , Y , Z , VTH )     *
                   *   AND STORE IN NUMBXB , NUMBYB , NUMBZB , NUMBVT  *
                   *                                                   *
                   *****************************************************
                   *
                   *
F914 BE   D065     START  LDX NUMZ
F917 A6   89 D040         LDA SEQXZ,X
F91B B7   D072            STA $D072
F91E C6   04              LDB #4              SET COUNTER TO 4
F920 8E   0000            LDX #0
F923 86   3E       NUDATA LDA #%00111110      BRING RD HIGH
F925 B7   9001            STA PIA2CA
F928 84   F7              ANDA #%11110111     BRING RD LOW
F92A B7   9001            STA PIA2CA
F92D 8A   08              ORA #%00001000      BRING RD HIGH
F92F B7   9001            STA PIA2CA
F932 B6   9001     WAIT1  LDA PIA2CA          WAIT FOR CONVERSION
F935 2A   FB              BPL WAIT1           TO COMPLETE
```

```
F937 86   36              LDA #%00110110      BRING RD LOW
F939 B7   9001            STA PIA2CA
F93C B6   9000            LDA PIA2DA
F93F 12                   NOP
F940 12                   NOP
F941 B6   9000            LDA PIA2DA          READ DATA
F944 A7   89 D020         STA NUMBXB,X        STORE DATA
F948 86   3E              LDA #%00111110
F94A B7   9001            STA PIA2CA
F94D 30   01              LEAX 1,X
F94F B6   D072            LDA $D072
F952 8A   20              ORA #%00100000      CLOCK COUNTER TO CONNECT
F954 B7   9002            STA PIA2DB          NEXT CHANNEL (X , Y , Z , VTH)
F957 BD   F6CC            JSR DELY4
F95A B6   D072            LDA $D072
F95D 84   0F              ANDA #%00001111
F95F B7   9002            STA PIA2DB
F962 108E 07D0            LDY #2000
F966 BD   F6D9            JSR DLY2
F969 5A                   DECB                HAS ALL 4 DATA BEEN COLLECTED
F96A 26   B7              BNE NUDATA          NO - CONTINUE COLLECTING
F96C B6   D072            LDA $D072
F96F BD   FE86            JSR DISPVZ          DISPLAY VTH
                    *
                    *
                    ***************************************************
                    *                                                 *
                    *   STEPPING MOTORS X Y & Z CONTROL ROUTINE .     *
                    *   THE NORMAL CONTROL SEQUENCE IS STEPPING MOTOR X *
                    *   FIRST THEN STEPPING  MOTOR Y  AND FINALLY MOTOR *
                    *   Z . MOTOR Z IS SEQUENCED FIRST PROVIDED THE   *
                    *   THRESHOLD VOLTAGE IS LESS    THEN THE MINIMUM *
                    *   THRESHOLD VOLTAGE SETTING .                   *
                    *   IF THE THRESHOLD VOLTAGE IS LESS    THEN THE  *
```

```
                   *   MINIMUM THRESHOLD SETTING THEN THE SYSTEM        *
                   *   DISABLES STEPPING MORORS X AND Y .               *
                   *                                                    *
                   ******************************************************
                   *
                   *
F972 BE   D023            LDX NUMBVT
F975 BC   D030            CMPX VTHMIN         CHECK IF VTH >= VTHMIN
F978 1022 01FD            LBHI STEPZ
                   *
                   ******************************************************
                   *                                                    *
                   *  MOTOR X AND MOTOR Y STEPPING SEQUENCE.            *
                   *  THIS ROUTINE CHECKS IF ANY STEP IS TO BE TAKEN    *
                   *  BY MOTORS X AND/OR Y. IF NONE THEN THEN THE       *
                   *  ROUTINE GOES TO CONTROL MOTOR Z. IF MOTOR  X      *
                   *  AND/OR Y ARE TO BE SEQUENCED THEN THE SYSTEM      *
                   *  FIRST CALCULATES THE SLOPE OF THE TRAVEL OF THE   *
                   *  MICROELECTRODE. IT ACCORDING SETS SEQUENCE        *
                   *  REPITITION REGISTERS AND SEQUENCES MOTORS X       *
                   *  AND/OR Y. WHEN THE MICROELECTRODE IS WITHIN A     *
                   *  FEW MICRONS OF ITS FINAL POSITION , THE SYSTEM    *
                   *  SCANS JOYSTICK INPUT AFTER EVERY STEP OF THE      *
                   *  STEPPER MOTOR AND CHECKS IF THE FINAL POSITION    *
                   *  HAS BEEN ALTERED OR NOT. THIS ROUTINE ENABLES     *
                   *  THE MICROELECTRODE TO FOLLOW THE MICROELECTRODE   *
                   *  VERY CLOSELY. ONCE THE DESIRED POSITION IN X-Y    *
                   *  PLANE HAS BEEN REACHED THE SYSTEM GOES ON TO      *
                   *  CONTROL MOTOR Z. THIS ROUTINE PERMITS THE MOTORS *
                   *  X AND Y TO BE SEQUENCED IN EITHER A CONSTANT      *
                   *  SPEED MODE OR AT A RAMPING SPEED MODE. THIS       *
                   *  ARRANGEMENT ENSURES THE MICROELECTRODE            *
                   *  REACHING ITS FINAL POSITION VERY QUICKLY WITHOUT *
                   *  ANY STEPS MISSED AT THE START OF THE STEPPING     *
```

```
                          *  SEQUENCE AND NO OVERSHOOT AT THE FINISH OF      *
                          *  THE STEPPING SEQUENCE.                           *
                          *                                                   *
                          ****************************************************
                          *
                          *
F97C 7F   D084                   CLR COUNTA
F97F 7F   D085                   CLR COUNTB
F982 B6   D020                   LDA NUMBXB
F985 B1   D032                   CMPA VTUL0X
F988 26   23                     BNE CALSTP
F98A B6   D021                   LDA NUMBYB
F98D B1   D033                   CMPA VTUL0Y
F990 1027 01E5                   LBEQ STEPZ
F994 25   05                     BLO CALYA
F996 B0   D033                   SUBA VTUL0Y
F999 20   06                     BRA RATOST
                          *
                          *
                          ***************************************************
                          *                                                 *
                          *  THE SYSTEM CALCULATES THE NUMBER OF STEPS      *
                          *  TO BE TAKEN BY STEPPER MOTORS X AND/OR Y.      *
                          *                                                 *
                          ***************************************************
                          *
                          *
F99B B6   D033            CALYA  LDA VTUL0Y
F99E B0   D021                   SUBA NUMBYB
F9A1 B7   D076            RATOST STA NUSEQY
F9A4 B7   D082                   STA NUSEY
F9A7 B7   D027                   STA NUMBY
F9AA 16   0124                   LBRA YSEQN
F9AD 25   08              CALSTP BLO CALNUX
```

```
F9AF B0   D032          SUBA VTUL0X
F9B2 B7   D026          STA NUMBX
F9B5 20   09            BRA CALY
F9B7 B6   D032   CALNUX LDA VTUL0X
F9BA B0   D020          SUBA NUMBXB
F9BD B7   D026          STA NUMBX
F9C0 B6   D021   CALY   LDA NUMBYB
F9C3 B1   D033          CMPA VTUL0Y
F9C6 25   0A            BLO CALNUY
F9C8 27   11            BEQ DETRTO
F9CA B0   D033          SUBA VTUL0Y
F9CD B7   D027          STA NUMBY
F9D0 20   09            BRA DETRTO
F9D2 B6   D033   CALNUY LDA VTUL0Y
F9D5 B0   D021          SUBA NUMBYB
F9D8 B7   D027          STA NUMBY
                 *
                 *
                 ************************************************
                 *                                              *
                 *  THIS ROUTINE CALCULATES THE SLOPE           *
                 *  OF THE TRAVEL OF THE MICROELECTRODE IN      *
                 *  X-Y PLANE.                                  *
                 *                                              *
                 ************************************************
                 *
                 *
F9DB 7F   D078   DETRTO CLR MURTIO
F9DE B6   D021          LDA NUMBYB
F9E1 B1   D033          CMPA VTUL0Y
F9E4 1027 0052          LBEQ RATIOA
F9E8 B6   D026          LDA NUMBX
F9EB B1   D027          CMPA NUMBY
F9EE 27   1E            BEQ RATIOC
```

```
F9F0 25   2C              BLO RATIOB
                   *
                   *
                   **************************************************
                   *                                                *
                   *   THIS ROUTINE PERMITS X:1 TRAVEL OF THE       *
                   *   MICROELECTRODE.                              *
                   *                                                *
                   **************************************************
                   *
                   *
F9F2 B7   D079            STA MURTIO+1
F9F5 B6   D027            LDA NUMBY
F9F8 B7   D074            STA MLRTIO
F9FB BD   F6AC            JSR RATIO
F9FE F7   D075            STB NUSEQX
FA01 F7   D081            STB NUSEX
FA04 86   01              LDA #1
FA06 B7   D076            STA NUSEQY
FA09 B7   D082            STA NUSEY
FA0C 20   35              BRA XSEQN
                   *
                   *
                   *************************************************
                   *                                               *
                   *   THIS ROUTINE PERMITS 1:1 OR 45 DEGREES      *
                   *   TRAVEL OF THE MICROELECTRODE.               *
                   *                                               *
                   *************************************************
                   *
                   *
FA0E 86   01       RATIOC LDA #1
FA10 B7   D075            STA NUSEQX
FA13 B7   D076            STA NUSEQY
```

```
FA16 B7    D081               STA NUSEX
FA19 B7    D082               STA NUSEY
FA1C 20    25                 BRA XSEQN
                 *
                 *
                 *********************************************
                 *                                           *
                 *   THIS ROUTINE PERMITS 1:Y TRAVEL OF THE  *
                 *   MICROELECTRODE ( SLOPE OF > 45 DEG. )   *
                 *                                           *
                 *********************************************
                 *
                 *
                 *
FA1E B7    D074  RATIOB STA MLRTIO
FA21 B6    D027           LDA NUMBY
FA24 B7    D079           STA MURTIO+1
FA27 BD    F6AC           JSR RATIO
FA2A F7    D076           STB NUSEQY
FA2D F7    D082           STB NUSEY
FA30 86    01             LDA #1
FA32 B7    D075           STA NUSEQX
FA35 B7    D081           STA NUSEX
FA38 20    09             BRA XSEQN
                 *
                 *
                 *********************************************
                 *                                           *
                 *   THIS ROUTINE PERMITS X:0 TRAVEL OF THE  *
                 *   MICROELECTRODE (TRAVEL IN X DIRECTION   *
                 *   ONLY).                                  *
                 *                                           *
                 *********************************************
                 *
```

```
                   *
FA3A B6   D026     RATIOA LDA NUMBX
FA3D B7   D075            STA NUSEQX
FA40 B7   D081            STA NUSEX
                   *
                   *
                   ************************************************
                   *                                              *
                   *  MOTOR X STEPPING SEQUENCE. THE SYSTEM       *
                   *  CHECKS IF THE NUMBER OF STEPS TO BE         *
                   *  TAKEN IS >5. IF IT IS GREATER THEN 5        *
                   *  THEN THE  MOTOR STARTS AT A CONSTANT        *
                   *  STEPPING SPEED OF 2 STEPS PER SEC FOR       *
                   *  FIRST FIVE STEPS AND THEN RAMPS TO THE      *
                   *  SPEED OF 15 STEPS/SEC. UNTIL ONLY FIVE      *
                   *  STEPS ARE LEFT. THIS ENSURES THE DESIRED    *
                   *  POSITION REACHED QUICKLY AND ALSO NO STEPS  *
                   *  MISSED AT THE START. THE LAST FIVE STEPS    *
                   *  THE SYSTEM SCANS THE JOYSTICK INPUT AFTER   *
                   *  EVERY STEP THUS SEQUENCING THE MOTOR AT     *
                   *  A CONSTANT SPEED OF 2 STEPS/SEC.. THIS      *
                   *  ENSURES NO OVERSHOOT AT THE FINISH OF THE   *
                   *  SEQUENCE AND ALSO THE MICROELECTRODE        *
                   *  FOLLOWING THE JOYSTICK VERY CLOSELY.        *
                   *                                              *
                   ************************************************
                   *
                   *
FA43 B6   D020     XSEQN  LDA NUMBXB
FA46 B1   D032            CMPA VTULOX
FA49 1022 002D            LBHI  SEQXCW
                   *
                   *
                   ***********************************************
```

```
                    *                                             *
                    *   COUNTER CLOCKWISE STEPPING SEQUENCE       *
                    *   FOR MOTOR X AT CONSTANT - RAMP SPEED      *
                    *                                             *
                    ***********************************************
                    *
                    *
FA4D BE   D069      XSEQ   LDX NUMX
FA50 BD   FEB7      XSEQB  JSR SEQXB
FA53 BD   FF3A             JSR STSPDX
FA56 7A   D032             DEC VTUL0X
FA59 B6   D026             LDA NUMBX
FA5C 81   05               CMPA #5
FA5E 1023 0045             LBLS MOTOXB
FA62 B6   D075             LDA NUSEQX
FA65 81   00               CMPA #0
FA67 1027 003C             LBEQ MOTOXB
FA6B 30   01               LEAX 1,X
FA6D BF   D069             STX NUMX
FA70 8C   0004             CMPX #4
FA73 26   DB               BNE XSEQB
FA75 BD   F72B             JSR SETXB
FA78 20   D3               BRA XSEQ
                    *
                    *
                    ************************************************
                    *                                              *
                    *  CLOCKWISE STEPPING SEQUENCE FOR MOTOR X     *
                    *  AT CONSTANT - RAMP SPEED.                   *
                    *                                              *
                    ************************************************
                    *
                    *
FA7A BE   D069      SEQXCW LDX NUMX
```

```
FA7D BD   FEBC     XSEQA  JSR SEQXA
FA80 BD   FF3A            JSR STSPDX
FA83 7C   D032            INC VTUL0X
FA86 B6   D026            LDA NUMBX
FA89 81   05              CMPA #5
FA8B 1023 001D            LBLS MOTOXA
FA8F B6   D075            LDA NUSEQX
FA92 81   00              CMPA #0
FA94 1027 0014            LBEQ MOTOXA
FA98 30   1F              LEAX -1,X
FA9A BF   D069            STX NUMX
FA9D 8C   FFFF            CMPX #-1
FAA0 26   DB              BNE XSEQA
FAA2 BD   F730            JSR SETXA
FAA5 20   D3              BRA SEQXCW
                   *
                   *
                   **********************************************
                   *                                            *
                   *  MOTOR X AND  Y SEQUENCE CONTROL.          *
                   *  (CONSTANT - RAMP SPEED MODE)              *
                   *                                            *
                   **********************************************
                   *
                   *
FAA7 BD   F7D5     MOTOXB JSR MOTOB
FAAA 20   03              BRA CHKNMY
FAAC BD   F7C0     MOTOXA JSR MOTOA
FAAF B6   D027     CHKNMY LDA NUMBY
FAB2 81   00              CMPA #0
FAB4 1026 0019            LBNE YSEQN
FAB8 B6   D026            LDA NUMBX
FABB 81   05              CMPA #5
FABD 22   09              BHI UPSEQX
```

```
FABF 81   00               CMPA #0
FAC1 1027 00B4             LBEQ STEPZ
FAC5 16   FE4C             LBRA START
FAC8 B6   D081      UPSEQX LDA NUSEX
FACB B7   D075             STA NUSEQX
FACE 16   FF72             LBRA XSEQN
                    *
                    *
                    *************************************************
                    *                                               *
                    *  MOTOR Y STEPPING SEQUENCE. THIS ROUTINE      *
                    *  CHECKS IF THE NUMBER OF STEPS TO BE TAKEN    *
                    *  BY MOTOR Y IS GREATER THEN FIVE. IF IT IS    *
                    *  THEN THE MOTOR STARTS AT A CONSTANT SPEED    *
                    *  OF 2 STEPS/SEC. FOR THE FIRST FIVE STEPS     *
                    *  AND THEN RAMPS TO 15 STEPS/SEC. UNTIL ONLY   *
                    *  FIVE STEPS ARE LEFT, OTHERWISE THE MOTOR     *
                    *  IS SEQUENCED AT A CONSTANT SPEED OF 2        *
                    *  STEPS/SEC..THIS ROUTINE ENSURES THAT NO      *
                    *  STEPS ARE MISSED AT THE START OF THE         *
                    *  SEQUENCE AND ALSO THE FINAL MICROELECTRODE   *
                    *  POSITION IS REACHED QUICKLY. FOR THE LAST    *
                    *  FIVE STEPS THE ROUTINE SCANS THE JOYSTICK    *
                    *  INPUT AFTER EACH STEP THUS SEQUENCING THE    *
                    *  MOTOR AT A CONSTANT SPEED OF 2 STEPS/SEC..   *
                    *  THIS ROUTINE ENSURES NO OVERSHOOT AND ALSO   *
                    *  THE MICROELECTRODE FOLLOWING THE JOYSTICK    *
                    *  CLOSELY.                                     *
                    *                                               *
                    *************************************************
                    *
                    *
FAD1 B6   D021      YSEQN  LDA NUMBYB
FAD4 B1   D033             CMPA VTUL0Y
```

```
FAD7 1022 002D            LBHI SEQYCW
                   *
                   *
                   ************************************************
                   *                                              *
                   *    COUNTER CLOCKWISE STEPPING SEQUENCE       *
                   *    FOR MOTOR Y IN CONSTANT-RAMP SPEED        *
                   *    MODE.                                     *
                   *                                              *
                   ************************************************
                   *
                   *
FADB BE   D067     YSEQ   LDX NUMY
FADE BD   FEE2     YSEQB  JSR SEQYB
FAE1 BD   FF4A            JSR STSPDY
FAE4 7A   D033            DEC VTUL0Y
FAE7 B6   D027            LDA NUMBY
FAEA 81   05              CMPA #5
FAEC 1023 0045            LBLS MOTOYB
FAF0 B6   D076            LDA NUSEQY
FAF3 81   00              CMPA #0
FAF5 1027 003C            LBEQ MOTOYB
FAF9 30   01              LEAX 1,X
FAFB BF   D067            STX NUMY
FAFE 8C   0004            CMPX #4
FB01 26   DB              BNE YSEQB
FB03 BD   F71F            JSR SETYB
FB06 20   D3              BRA YSEQ
                   *
                   *
                   ************************************************
                   *                                              *
                   *   CLOCKWISE STEPPING SEQUENCE FOR MOTOR Y    *
                   *                                              *
```

```
                    ***********************************************
                    *
                    *
FB08 BE   D067      SEQYCW LDX NUMY
FB0B BD   FEE7      YSEQA  JSR SEQYA
FB0E BD   FF4A             JSR STSPDY
FB11 7C   D033             INC VTUL0Y
FB14 B6   D027             LDA NUMBY
FB17 81   05               CMPA #5
FB19 1023 001D             LBLS MOTOYA
FB1D B6   D076             LDA NUSEQY
FB20 81   00               CMPA #0
FB22 1027 0014             LBEQ MOTOYA
FB26 30   1F               LEAX -1,X
FB28 BF   D067             STX NUMY
FB2B 8C   FFFF             CMPX #-1
FB2E 26   DB               BNE YSEQA
FB30 BD   F724             JSR SETYA
FB33 20   D3               BRA SEQYCW
                    *
                    *
                    ***********************************************
                    *                                             *
                    *   MOTOR X AND Y STEPPING SEQUENCE CONTROL   *
                    *   ( CONSTANT - RAMP SPEED MODE )            *
                    *                                             *
                    ***********************************************
                    *
                    *
FB35 BD   FF5A      MOTOYB JSR MOTOC
FB38 20   03               BRA CHKNMX
FB3A BD   FF6F      MOTOYA JSR MOTOD
FB3D B6   D027      CHKNMX LDA NUMBY
FB40 81   05               CMPA #5
```

```
FB42 22   25               BHI CKNHX
FB44 81   00               CMPA #0
FB46 26   09               BNE CKNX
FB48 B6   D026             LDA NUMBX
FB4B 81   00               CMPA #0
FB4D 1027 0028             LBEQ STEPZ
FB51 B6   D026      CKNX   LDA NUMBX
FB54 81   05               CMPA #5
FB56 1023 FDBA             LBLS START
FB5A B6   D081      UPDTSQ LDA NUSEX
FB5D B7   D075             STA NUSEQX
FB60 B6   D082             LDA NUSEY
FB63 B7   D076             STA NUSEQY
FB66 16   FEDA             LBRA XSEQN
FB69 B6   D026      CKNHX  LDA NUMBX
FB6C 81   00               CMPA #0
FB6E 26   EA               BNE UPDTSQ
FB70 B6   D082             LDA NUSEY
FB73 B7   D076             STA NUSEQY
FB76 16   FF58             LBRA YSEQN
                    *
                    *
                    *************************************************
                    *                                               *
                    *    STEPPER MOTOR Z CONTROL ROUTINE            *
                    *   THIS ROUTINE INITIALLY CHECKS IF THE INTRA- *
                    *   CELLULAR POTENTIAL IS LESS THAN THE CELL    *
                    *   THRESHOLD VOLTAGE. IF IT IS LESS THAN THE   *
                    *   THRESHOLD CELL VOLTAGE THE SYSTEM DISABLES  *
                    *   STEPPER MOTOR Z, DISPLAYS THE PRESENT 'Z'   *
                    *   POSITION OF THE MICROELECTRODE AND THE INTRA-*
                    *   CELLULAR POTENTIAL, ENABLES THE AUDIBLE/    *
                    *   VISUAL ALARM AND GETS INTO LOW POWER 'HALT' *
                    *   MODE.                                       *
```

```
                   *   FOR INTRA-CELLULAR POTENTIAL GREATER THAN     *
                   *   THE CELL THRESHOLD VOLTAGE, THE 'Z' MOTOR IS  *
                   *   SEQUENCED ONE STEP AT A TIME. THE             *
                   *   MICROELECTRODE POSITION IN THE 'Z' PLANE  IS  *
                   *   DISPLAYED AND THE INTRACELLULAR POTENTIAL     *
                   *   MONITORED. AS LONG AS THE INTRA-CELLULAR      *
                   *   POTENTIAL IS GREATER THAN THE CELL THRESHOLD  *
                   *   POTENTIAL THE ABOVE ROUTINE IS CONTINUED      *
                   *   UNTIL ALL THE STEPS BY MOTOR Z IS TAKEN. IF   *
                   *   THE INTRA-CELLULAR POTENTIAL IS G.S AS VTMIN, *
                   *   SYSTEM CAUSES ALL INPUTS (X,Y,Z,CELL POT.)    *
                   *   TO BE MONITORED AGAIN AND THE COMPLETE X,Y,Z  *
                   *   MOTORS CONTROL ROUTINE REPEATED. IF THE INTRA-*
                   *   CELLULAR POTENTIAL IS LESS THAN VTMIN THE     *
                   *   THE SYSTEM                                    *
                   *   KEEPS MOTORS X AND Y DISABLED AND ONLY MOTOR  *
                   *   Z INPUT AND INTRA-CELLULAR POTENTIAL IS       *
                   *   MONITORED. IF THERE IS A CHANGE IN THE MOTOR  *
                   *   Z INPUT , THE ABOVE MOTOR Z CONTROL ROUTINE   *
                   *   IS REPEATED WITH THE SYSTEM COMPARING THE     *
                   *   INTRA-CELLULAR POTENTIAL WITH THE CELL        *
                   *   THRESHOLD VOLTAGE AFTER EACH STEP.            *
                   *                                                 *
                   *       THE SYSTEM CAN BE FORCED TO COME OUT OF   *
                   *   THE LOW POWER HALT MODE EITHER VIA KEYBOARD   *
                   *   INTERRUPT ROUTINE OR BY PRESSING THE "FORCED  *
                   *   PENETRATION" KEY ON THE KEYBOARD. THIS CAUSES *
                   *   THE SYSTEM TO GO INTO JOYSTICK MODE CONTROL   *
                   *   OF STEPPER MOTOR Z.                           *
                   *                                                 *
                   ***************************************************
                   *
                   *
FB79 BE   D023     STEPZ  LDX NUMBVT
```

```
FB7C BC   D02E              CMPX VTHMAX
FB7F 1022 0177              LBHI SYSHLT
FB83 F6   D022              LDB NUMBZB
FB86 F1   D034              CMPB VTUL0Z
FB89 1027 FD87              LBEQ START
FB8D F1   D034       SCANZ  CMPB VTUL0Z
FB90 1022 0086              LBHI MOTZA
FB94 1027 012A              LBEQ READZ
FB98 F6   D034              LDB VTUL0Z
FB9B F0   D022              SUBB NUMBZB
FB9E 5C                     INCB
FB9F F7   D028              STB NUMBZ
FBA2 F7   D029              STB NUMBZ0
FBA5 C1   0A                CMPB #10
FBA7 1022 0038              LBHI RMPZB
                     *
                     *
                     **************************************************
                     *                                                *
                     *  COUNTER CLOCKWISE CONTROL OF MOTOR Z IN       *
                     *  CONSTANT SPEED MODE WITH SPEED OF TWO STEPS   *
                     *  PER SEC.                                      *
                     *                                                *
                     **************************************************
                     *
                     *
FBAB BE   D065       CONTZB LDX NUMZ
FBAE BD   FDA6       NXSTZB JSR SEQZ
FBB1 BD   FF21              JSR READVT
FBB4 10BE D023              LDY NUMBVT
FBB8 10BC D030              CMPY VTHMIN
FBBC 1022 00D0              LBHI CNRLZB
FBC0 BD   F6D5              JSR DELY2
FBC3 7A   D028              DEC NUMBZ
```

```
FBC6 27   12                BEQ SETREF
FBC8 7A   D02C     CSTZB    DEC MULTZ
FBCB 30   01                LEAX 1,X
FBCD BF   D065              STX NUMZ
FBD0 8C   0004              CMPX #4
FBD3 26   D9                BNE NXSTZB
FBD5 BD   F737              JSR SETZB
FBD8 20   D1                BRA CONTZB
                   *
                   *
FBDA F6   D022     SETREF LDB NUMBZB
FBDD F7   D034            STB VTUL0Z
FBE0 16   FD31            LBRA START
                   *
                   *
                   *************************************************
                   *                                               *
                   *   COUNTER CLOCKWISE RAMP SPEED CONTROL        *
                   *   ROUTINE FOR MOTOR Z WITH SPEED INCREASING   *
                   *   FROM 2 STEPS/SEC TO 15 STEPS/SEC AND        *
                   *   DECREASING TO 2 STEPS/SEC .                 *
                   *                                               *
                   *************************************************
                   *
                   *
FBE3 7F   D050     RMPZB  CLR COUNTR
FBE6 BE   D065     CNRZB  LDX NUMZ
FBE9 BD   FDA6     NSRZB  JSR SEQZ
FBEC BD   FF21            JSR READVT
FBEF 10BE D023            LDY NUMBVT
FBF3 10BC D030            CMPY VTHMIN
FBF7 1022 0095            LBHI CNRLZB
FBFB 7A   D028            DEC NUMBZ
FBFE F6   D028            LDB NUMBZ
```

```
FC01 C1   05              CMPB #5
FC03 27   C3              BEQ CSTZB
FC05 7A   D02C     CSTZBA DEC MULTZ
FC08 BD   F6DE            JSR MCOUNT
FC0B 30   01              LEAX 1,X
FC0D BF   D065            STX NUMZ
FC10 8C   0004            CMPX #4
FC13 26   D4              BNE NSRZB
FC15 BD   F737            JSR SETZB
FC18 20   CC              BRA CNRZB
                   *
                   *
                   **********************************************
                   *                                            *
                   *   MOTOR Z CLOCKWISE CONTROL ROUTINE  WITH  *
                   *   INTRA-CELLULAR POTENTIAL GREATER THAN    *
                   *   CELL THRESHOLD VOLTAGE.                  *
                   *                                            *
                   **********************************************
                   *
                   *
FC1A F0   D034     MOTZA  SUBB VTUL0Z
FC1D 5C                   INCB
FC1E F7   D028            STB NUMBZ
FC21 F7   D029            STB NUMBZ0
FC24 C1   0A              CMPB #10
FC26 1022 002F            LBHI RMPZA
                   *
                   *
                   *********************************************
                   *                                           *
                   *  MOTOR Z CLOCKWISE CONTROL ROUTINE AT     *
                   *  CONSTANT STEPPING SPEED OF 2 STEPS/SEC.  *
                   *                                           *
```

```
                        **********************************************
                        *
                        *
FC2A BE   D065          CONTZA LDX NUMZ
FC2D BD   FDA6          NXSTZA JSR SEQZ
FC30 BD   FF21                 JSR READVT
FC33 10BE D023                 LDY NUMBVT
FC37 10BC D030                 CMPY VTHMIN
FC3B 1022 006A                 LBHI CNRLZA
FC3F BD   F6D5                 JSR DELY2
FC42 7A   D028                 DEC NUMBZ
FC45 27   93                   BEQ SETREF
FC47 7C   D02C          CSTZA  INC MULTZ
FC4A 30   1F                   LEAX -1,X
FC4C BF   D065                 STX NUMZ
FC4F 8C   FFFF                 CMPX #-1
FC52 26   D9                   BNE NXSTZA
FC54 BD   F73C                 JSR SETZA
FC57 20   D1                   BRA CONTZA
                        *
                        *
                        *********************************************
                        *                                           *
                        *   MOTOR Z CLOCKWISE STEPPING SEQUENCE     *
                        *   IN RAMP SPEED MODE WITH SPEED MAXIMUM   *
                        *   SPEED OF 15 STEPS/SEC.                  *
                        *                                           *
                        *********************************************
                        *
                        *
FC59 7F   D050          RMPZA  CLR COUNTR
FC5C BE   D065          CNRZA  LDX NUMZ
FC5F BD   FDA6          NSRZA  JSR SEQZ
FC62 BD   FF21                 JSR READVT
```

```
FC65 10BE D023           LDY NUMBVT
FC69 10BC D030           CMPY VTHMIN
FC6D 1022 0038           LBHI CNRLZA
FC71 7A   D028           DEC NUMBZ
FC74 F6   D028           LDB NUMBZ
FC77 C1   05             CMPB #5
FC79 27   CC             BEQ CSTZA
FC7B 7C   D02C    CSTZAA INC MULTZ
FC7E BD   F6DE           JSR MCOUNT
FC81 30   1F             LEAX -1,X
FC83 BF   D065           STX NUMZ
FC86 8C   FFFF           CMPX #-1
FC89 26   D4             BNE NSRZA
FC8B BD   F73C           JSR SETZA
FC8E 20   CC             BRA CNRZA
                   *
                   *
                   ************************************************
                   *                                              *
                   *   CONTROL ROUTINE                            *
                   *   THIS ROUTINE COMPARES THE INTRA-CELLULAR   *
                   *   POTENTIAL WITH THE CELL THRESHOLD VOLTAGE  *
                   *   , FOR INTRA-CELLULAR POTENTIAL LESS THAN   *
                   *   THE CELL THRESHOLD VOLTAGE THE SYSTEM      *
                   *   GOES INTO LOW POWER HALT MODE OTHERWISE    *
                   *   THE ABOVE ROUTINE IS CONTINUED.            *
                   *                                              *
                   ************************************************
                   *
                   *
FC90 10BC D02E    CNRLZB CMPY VTHMAX
FC94 1022 0043           LBHI SYSHTB
FC98 7A   D028           DEC NUMBZ
FC9B 27   25             BEQ READZ
```

```
FC9D F6   D028              LDB NUMBZ
FCA0 C1   05                CMPB #5
FCA2 1027 FF22              LBEQ CSTZB
FCA6 16   FF5C              LBRA CSTZBA
                     *
                     *
FCA9 10BC D02E       CNRLZA CMPY VTHMAX
FCAD 1022 003E              LBHI SYSHTA
FCB1 7A   D028              DEC NUMBZ
FCB4 27   0C                BEQ READZ
FCB6 F6   D028              LDB NUMBZ
FCB9 C1   05                CMPB #5
FCBB 1027 FF88              LBEQ CSTZA
FCBF 16   FFB9              LBRA CSTZAA
                     *
                     *
                     ************************************************
                     *                                              *
                     *   THIS ROUTINE READS THE "Z" MOTOR CONTROL   *
                     *   JOYSTICK INPUT AND RETURNS TO REPEAT       *
                     *   MOTOR Z CONTROL ROUTINE.                   *
                     *                                              *
                     ************************************************
                     *
                     *
FCC2 F6   D022       READZ  LDB NUMBZB
FCC5 F7   D034              STB VTULOZ
FCC8 BE   D065              LDX NUMZ
FCCB E6   89 D040           LDB SEQXZ,X
FCCF F7   D072              STB $D072
FCD2 BD   FF0D              JSR READZI
FCD5 F6   D022              LDB NUMBZB
FCD8 16   FEB2              LBRA SCANZ
                     *
```

```
                        *
                        ***********************************************
                        *                                             *
                        *   HALT ROUTINE. THIS ROUTINE DISABLES       *
                        *   MOTOR Z , ENABLES THE AUDIBLE/VISUAL      *
                        *   ALARM AND GOES INTO LOW POWER HALT MODE.  *
                        *                                             *
                        ***********************************************
                        *
                        *
FCDB F6    D029         SYSHTB LDB NUMBZ0
FCDE F0    D028                SUBB NUMBZ
FCE1 F7    D092                STB STPZ
FCE4 F6    D034                LDB VTUL0Z
FCE7 F0    D092                SUBB STPZ
FCEA F7    D034         STORE0 STB VTUL0Z
FCED 20    0B                  BRA SYSHLT
                        *
                        *
FCEF F6    D029         SYSHTA LDB NUMBZ0
FCF2 F0    D028                SUBB NUMBZ
FCF5 FB    D034                ADDB VTUL0Z
FCF8 20    F0                  BRA STORE0
                        *
                        *
FCFA C6    04           SYSHLT LDB #4
FCFC F7    D090                STB $D090
FCFF C6    FF           BEEPC0 LDB #255
FD01 8A    10           BEEP   ORA #%00010000
FD03 B7    9002                STA PIA2DB
FD06 BD    F6CC                JSR DELY4
FD09 84    EF                  ANDA #%11101111
FD0B B7    9002                STA PIA2DB
FD0E BD    F6CC                JSR DELY4
```

```
FD11 5A                     DECB
FD12 26   ED                BNE BEEP
FD14 108E 4E20              LDY #20000
FD18 BD   F6D9              JSR DLY2
FD1B 7A   D090              DEC $D090
FD1E 26   DF                BNE BEEPCO
FD20 BE   D065              LDX NUMZ
FD23 E6   89 D040           LDB SEQXZ,X
FD27 F7   D072              STB $D072
FD2A 20   FE         HALT   BRA HALT
                     *
                     *
                     ********************************************
                     *                                          *
                     *   FORCED PENETRATION ROUTINE.            *
                     *   THE SYSTEM GOES INTO THIS ROUTINE ONCE *
                     *   THE FORCED PENETRATION KEY (.P) ON THE *
                     *   KEYBOARD IS PRESSED. THIS ROUTINE ENABLES *
                     *   THE MOTOR Z TO BE CONTROLLED VIA JOYSTICK *
                     *   EVEN THOUGH THE INTRA-CELLULAR POTENTIAL *
                     *   IS LESS THAN THE CELL THRESHOLD VOLTAGE. *
                     *                                          *
                     ********************************************
                     *
                     *
FD2C BD   FF0D       FORCET JSR READZI
FD2F F6   D022              LDB NUMBZB
FD32 F1   D034              CMPB VTUL0Z
FD35 1022 002E              LBHI MOTFZA
FD39 27   F1                BEQ FORCET
                     *
                     *
                     ********************************************
                     *                                          *
```

```
                   *   THIS ROUTINE CAUSES THE MOTOR Z TO BE      *
                   *   CONTROLLED IN COUNTER CLOCKWISE DIRECTION *
                   *   WITH THE INTRA-CELLULAR POTENTIAL LESS     *
                   *   THAN THE CELL THRESHOLD VOLTAGE IN         *
                   *   CONSTANT SPEED MODE.                       *
                   *                                              *
                   **********************************************
                   *
                   *
FD3B F6   D034              LDB VTUL0Z
FD3E F0   D022              SUBB NUMBZB
FD41 5C                     INCB
FD42 F7   D028              STB NUMBZ
FD45 BE   D065     CNTRZ   LDX NUMZ
FD48 BD   FDA6     NXTRZ   JSR SEQZ
FD4B BD   F6D5              JSR DELY2
FD4E 7A   D028              DEC NUMBZ
FD51 1027 0039              LBEQ UPDATE
FD55 7A   D02C              DEC MULTZ
FD58 30   01                LEAX 1,X
FD5A BF   D065              STX NUMZ
FD5D 8C   0004              CMPX #4
FD60 26   E6                BNE NXTRZ
FD62 BD   F737              JSR SETZB
FD65 20   DE                BRA CNTRZ
                   *
                   *
                   *********************************************
                   *                                           *
                   *   THIS ROUTINE CAUSES THE MOTOR Z TO BE   *
                   *   CONTROLLED IN CLOCKWISE DIRECTION IN    *
                   *   CONSTANT SPEED MODE WITH THE INTRA-     *
                   *   CELLULAR POTENTIAL LESS THAN THE CELL   *
                   *   THRESHOLD VOLTAGE.                      *
```

```
                        *                                          *
                        ********************************************
                        *
                        *
FD67 F0   D034          MOTFZA SUBB VTULOZ
FD6A 5C                        INCB
FD6B F7   D028                 STB NUMBZ
FD6E BE   D065          CNTFZ  LDX NUMZ
FD71 BD   FDA6          NXTFZ  JSR SEQZ
FD74 BD   F6D5                 JSR DELY2
FD77 7A   D028                 DEC NUMBZ
FD7A 27   12                   BEQ UPDATE
FD7C 7C   D02C                 INC MULTZ
FD7F 30   1F                   LEAX -1,X
FD81 BF   D065                 STX NUMZ
FD84 8C   FFFF                 CMPX #-1
FD87 26   E8                   BNE NXTFZ
FD89 BD   F73C                 JSR SETZA
FD8C 20   E0                   BRA CNTFZ
                        *
                        *
FD8E F6   D022          UPDATE LDB NUMBZB
FD91 F7   D034                 STB VTULOZ
FD94 BD   FF21                 JSR READVT
FD97 10BE D023                 LDY NUMBVT
FD9B 10BC D02E                 CMPY VTHMAX
FD9F 1022 FF89                 LBHI FORCET
FDA3 16   FF1C                 LBRA READZ
                        *
                        *
                        ********************************************
                        *                                          *
                        *     SUBROUTINE SEQZ                      *
                        *   THIS ROUTINE SEQUENCES THE STEPPER MOTOR   *
```

```
                  *   Z IN EITHER CLOCKWISE OR COUNTER CLOCKWISE *
                  *   DIRECTION DEPENDING UPON THE JOYSTICK      *
                  *   INPUT, CALCULATES THE MICROELECTRODE IN Z  *
                  *   DIRECTION AND DISPLAYS THE MICROELECTRODE  *
                  *   POSITION IN Z DIRECTION.                   *
                  *                                              *
                  ************************************************
                  *
                  *
FDA6 A6   89 D040 SEQZ   LDA SEQXZ,X
FDAA B7   9002           STA PIA2DB
FDAD 36   12             PSHU X,A
FDAF B6   D02C           LDA MULTZ
FDB2 F6   D02D           LDB MULTPD
FDB5 3D                  MUL
FDB6 FD   D035           STD ANSHEX
FDB9 108E 0008           LDY #8
FDBD BD   FDFF           JSR HEXDEC
FDC0 37   02             PULU A
FDC2 BD   FEA0           JSR DISPLZ
FDC5 37   10             PULU X
FDC7 39                  RTS
                  *
                  *
                  ******************************************************
                  *                                                    *
                  *     SUBROUTINE   SCAN                              *
                  *    THIS  ROUTINE  SCANS  THE INPUT AND READ EITHER *
                  *    X OR Y OR Z OR VTH.                             *
                  *                                                    *
                  ******************************************************
                  *
                  *
FDC8 BD   FF2C    SCAN   JSR CLK      PROVIDE CLOCK  PULSE
```

```
FDCB BD   F6CC               JSR DELY4
FDCE 5A                      DECB
FDCF 26   F7                 BNE SCAN
FDD1 36   02                 PSHU A
FDD3 BD   F6D5               JSR DELY2
FDD6 86   3E                 LDA #%00111110      TAKE RD HIGH
FDD8 B7   9001               STA PIA2CA
FDDB 84   F7                 ANDA #%11110111     TAKE RD LOW
FDDD B7   9001               STA PIA2CA
FDE0 8A   08                 ORA #%00001000      TAKE RD HIGH
FDE2 B7   9001               STA PIA2CA
FDE5 B6   9001        WAIT2  LDA PIA2CA
FDE8 2A   FB                 BPL WAIT2
FDEA 86   36                 LDA #%00110110      TAKE RD LOW
FDEC B7   9001               STA PIA2CA
FDEF F6   9000               LDB PIA2DA          READ DATA
FDF2 12                      NOP
FDF3 12                      NOP
FDF4 F6   9000               LDB PIA2DA
FDF7 86   3E                 LDA #%00111110
FDF9 B7   9001               STA PIA2CA
FDFC 37   02                 PULU A
FDFE 39                      RTS
                      *
                      *
                      **************************************************
                      *                                                *
                      *     SUBROUTINE  HEXBCD                         *
                      *    THIS ROUTINE CONVERTS HEX  NUMBER TO BCD    *
                      *    EQUIVALENT AND STORES THE CONVERTED THE     *
                      *    IN CORRESPONDING DIGITS.                    *
                      *                                                *
                      **************************************************
                      *
```

```
                             *
FDFF 36    02                HEXDEC PSHU A
FE01 7F    D038                     CLR ANSDEC+1
FE04 7F    D037                     CLR ANSDEC
FE07 C6    10                       LDB #16
FE09 F7    D051                     STB NUMBER
FE0C B6    D038              BEGIN  LDA ANSDEC+1
FE0F 1F    89                       TFR A,B
FE11 84    0F                       ANDA #%00001111
FE13 81    05                       CMPA #$05
FE15 2D    02                       BLT CONT1
FE17 CB    03                       ADDB #$03
FE19 1F    98                CONT1  TFR B,A
FE1B 84    F0                       ANDA #%11110000
FE1D 81    50                       CMPA #$50
FE1F 25    02                       BLO CONT2
FE21 CB    30                       ADDB #$30
FE23 F7    D038              CONT2  STB ANSDEC+1
FE26 B6    D037                     LDA ANSDEC
FE29 1F    89                       TFR A,B
FE2B 84    0F                       ANDA #%00001111
FE2D 81    05                       CMPA #$05
FE2F 2D    02                       BLT CONT3
FE31 CB    03                       ADDB #$03
FE33 1F    98                CONT3  TFR B,A
FE35 84    F0                       ANDA #%11110000
FE37 81    50                       CMPA #$50
FE39 25    02                       BLO SHIFT
FE3B CB    30                       ADDB #$30
FE3D F7    D037              SHIFT  STB ANSDEC
FE40 78    D036                     ASL ANSHEX+1
FE43 79    D035                     ROL ANSHEX
FE46 79    D038                     ROL ANSDEC+1
FE49 79    D037                     ROL ANSDEC
```

```
FE4C 7A    D051            DEC NUMBER
FE4F 26    BB              BNE BEGIN
FE51 F6    D038            LDB ANSDEC+1
FE54 C4    0F              ANDB #%00001111
FE56 E7    A9 D000         STB DIGT1,Y
FE5A 31    21              LEAY 1,Y
FE5C F6    D038            LDB ANSDEC+1
FE5F C4    F0              ANDB #%11110000
FE61 54                    LSRB
FE62 54                    LSRB
FE63 54                    LSRB
FE64 54                    LSRB
FE65 E7    A9 D000         STB DIGT1,Y
FE69 31    21              LEAY 1,Y
FE6B F6    D037            LDB ANSDEC
FE6E C4    0F              ANDB #%00001111
FE70 E7    A9 D000         STB DIGT1,Y
FE74 31    21              LEAY 1,Y
FE76 F6    D037            LDB ANSDEC
FE79 C4    F0              ANDB #%11110000
FE7B 54                    LSRB
FE7C 54                    LSRB
FE7D 54                    LSRB
FE7E 54                    LSRB
FE7F E7    A9 D000         STB DIGT1,Y
FE83 37    02              PULU A
FE85 39                    RTS
                    *
                    *
                    ***********************************************
                    *                                             *
                    *     SUBROUTINE  DISPVT                      *
                    *   THIS ROUTINE CONVERTS VTH READING TO      *
                    *    BCD NUMBER AND DISPLAYS THE VTH VALUE.   *
```

```
                         *                                                 *
                         ***************************************************
                         *
                         *
FE86 36    12            DISPVZ PSHU X,A
FE88 B6    D023                 LDA NUMBVT
FE8B C6    01                   LDB #1             GET THE MULTIPLICAND
FE8D 3D                         MUL
FE8E FD    D035                 STD ANSHEX        STORE TRUE  VALUE
FE91 108E  000C                 LDY #$0C
FE95 BD    FDFF                 JSR HEXDEC         CONVERT TO BCD AND DISPLAY
FE98 37    02                   PULU A
FE9A BD    FEA0                 JSR DISPLZ
FE9D 37    10                   PULU X
FE9F 39                         RTS
                         *
                         *
                         **************************************************
                         *                                                *
                         *  SUBROUTINE DISPLZ.                            *
                         *  THIS ROUTINE DISPLAYS THE THRESHOLD           *
                         *  AND THE ACTUAL PENETRATION INTO THE CELL.     *
                         *                                                *
                         **************************************************
                         *
                         *
FEA0 8A    80            DISPLZ ORA #%10000000      TAKE MODE HIGH
FEA2 B7    9002                 STA PIA2DB
FEA5 C6    D0                   LDB #%11010000      HEX DECODING
FEA7 F7    C008                 STB DISP2
FEAA 84    7F                   ANDA #%01111111     TAKE MODE LOW
FEAC B7    9002                 STA PIA2DB
FEAF 36    02                   PSHU A
FEB1 BD    F70D                 JSR NXDGTZ          DISPLAY DIGITS
```

```
FEB4 37   02                PULU A
FEB6 39                     RTS
                   *
                   *
                   **************************************************
                   *                                                *
                   *    SUBROUTINE SEQXA AND SEQXB                  *
                   *    CLOCKWISE AND COUNTER CLOCKWISE STEPPING    *
                   *    SEQUENCE FOR MOTOR X. THIS ALSO CALCULATES  *
                   *    THE MICROELECTRODE MOVEMENT IN THE X        *
                   *    DIRECTION AND DISPLAYS THE VALUE IN MICRONS *
                   *                                                *
                   **************************************************
                   *
                   *
FEB7 7A   D02A     SEQXB  DEC MULTX
FEBA 20   03              BRA SEQX
FEBC 7C   D02A     SEQXA  INC MULTX
FEBF A6   89 D040  SEQX   LDA SEQXZ,X     SET THE STEPPING SEQ.
FEC3 BA   D070            ORA $D070
FEC6 B7   8002            STA PIA1DB
FEC9 B6   D02A            LDA MULTX       CAL. THE X DISPLACEMENT
FECC F6   D02D            LDB MULTPD      AND DISPLAY
FECF 3D                   MUL
FED0 FD   D035            STD ANSHEX
FED3 36   10              PSHU X
FED5 108E 0000            LDY #0
FED9 BD   FDFF            JSR HEXDEC      DISPL. DISPLACEMENT X IN + DIR.
FEDC BD   F6F5            JSR DISPL1
FEDF 37   10              PULU X
FEE1 39                   RTS
                   *
                   *
                   ****************************************************
                   *                                                  *
                   *   SUBROUTINE SEQYB AND SEQYB                     *
                   *   CLOCKWISE AND COUNTER CLOCKWISE STEPPING       *
                   *   SEQUENCE FOR MOTOR Y. THE ROUTINE CALCULATES   *
                   *   THE MICROELECTRODE MOVEMENT IN THE Y DIRECTION *
                   *   AND DISPLAYS THE VALUE IN MICRONS.             *
                   *                                                  *
                   ****************************************************
                   *
                   *
FEE2 7A   D02B     SEQYB  DEC MULTY
FEE5 20   03              BRA SEQYC
FEE7 7C   D02B     SEQYA  INC MULTY
FEEA A6   89 D044  SEQYC  LDA SEQY,X
FEEE BA   D071            ORA $D071
FEF1 B7   8002            STA PIA1DB
FEF4 B6   D02B            LDA MULTY
FEF7 F6   D02D            LDB MULTPD
FEFA 3D                   MUL
FEFB FD   D035            STD ANSHEX
FEFE 36   10              PSHU X
FF00 108E 0004            LDY #4
FF04 BD   FDFF            JSR HEXDEC
FF07 BD   F6F5            JSR DISPL1
FF0A 37   10              PULU X
FF0C 39                   RTS
                   *
                   *
                   **************************************************
                   *                                                *
                   *   SUBROUTINE READZI                            *
                   *   THIS ROUTINE READS THE SETTING ON Z POT.     *
                   *   AND RESETS THE ANALOG MUX. TO CONNECT        *
                   *   CHANNEL X.                                   *
```

```
                     *                                                  *
                     ****************************************************
                     *
                     *
FF0D C6    02        READZI LDB #2
FF0F BD    FDC8             JSR SCAN               READ Z
FF12 F7    D022             STB NUMBZB             AND STORE IN Z BUFFER
FF15 C6    02               LDB #2
FF17 BD    FF2C      PULS1  JSR CLK               RESET ANALOG MUX.
FF1A BD    F6CC             JSR DELY4
FF1D 5A                     DECB
FF1E 26    F7               BNE PULS1
FF20 39                     RTS
                     *
                     *
                     ****************************************************
                     *                                                  *
                     *    SUBROUTINE READVT.                            *
                     *    THIS ROUTINE READS THE THRESHOLD VOLTAGE      *
                     *    AND RESETS THE ANALOG MUX. TO CONNECT         *
                     *    CHANNEL X.                                    *
                     *                                                  *
                     ****************************************************
                     *
                     *
FF21 C6    03        READVT LDB #3       READ VTH AND STORE IN NUMBVT
FF23 BD    FDC8             JSR SCAN
FF26 F7    D023             STB NUMBVT
FF29 BD    FE86             JSR DISPVZ
FF2C 8A    20        CLK    ORA #%00100000
FF2E B7    9002             STA PIA2DB
FF31 BD    F6CC             JSR DELY4
FF34 84    DF               ANDA #%11011111
FF36 B7    9002             STA PIA2DB
```

```
FF39 39                   RTS
                   *
                   *
                   ***************************************************
                   *                                                 *
                   *   SUBROUTINE STSPDX.                            *
                   *   THIS ROUTINE ENABLES EITHER A CONSTANT        *
                   *   SPEED STEPPING SEQUENCE OF 2 STEPS/SEC.       *
                   *   OR A RAMP STEPPING SEQUENCE OF 15 STEPS/      *
                   *   SEC. FOR MOTOR X.                             *
                   *                                                 *
                   ***************************************************
                   *
                   *
FF3A 7C   D084     STSPDX INC COUNTA
FF3D F6   D084            LDB COUNTA
FF40 BD   FF84            JSR MCONTA
FF43 7A   D026            DEC NUMBX
FF46 7A   D075            DEC NUSEQX
FF49 39                   RTS
                   *
                   *
                   **************************************************
                   *                                                *
                   *   SUBROUTINE STSPDY.                           *
                   *   THIS ROUTINE ENABLES EITHER A CONSTANT       *
                   *   STEPPING SPEED OF 2 STEPS/SEC. OR A          *
                   *   RAMP STEPPING SEQUENCE OF 15 STEPS/SEC.      *
                   *   FOR MOTOR Y.                                 *
                   *                                                *
                   **************************************************
                   *
                   *
FF4A 7C   D085     STSPDY INC COUNTB
```

```
FF4D F6   D085              LDB COUNTB
FF50 BD   FF84              JSR MCONTA
FF53 7A   D027              DEC NUMBY
FF56 7A   D076              DEC NUSEQY
FF59 39                     RTS
                  *
                  *
                  ************************************************
                  *                                              *
                  *   SUBROUTINE  MOTOC.                         *
                  *   THIS ROUTINE IS USED TO UPDATE SEQ. Y      *
                  *   COUNTER REGISTER AND THE $D070 BUFFER      *
                  *   SO THAT NO STEPS ARE MISSED WHILE          *
                  *   SEQUENCING MOTOR Y IN COUNTER CLOCK        *
                  *   WISE DIRECTION.                            *
                  *                                              *
                  ************************************************
                  *
                  *
FF5A A6   89 D044 MOTOC     LDA SEQY,X
FF5E B7   D070              STA $D070
FF61 30   01                LEAX 1,X
FF63 BF   D067              STX NUMY
FF66 8C   0004              CMPX #4
FF69 26   03                BNE NYBOK
FF6B BD   F71F              JSR SETYB
FF6E 39           NYBOK     RTS
                  *
                  *
                  *************************************************
                  *                                               *
                  *   SUBROUTINE  MOTOD.                          *
                  *   THIS ROUTINE IS USED TO UPDATE SEQ. Y       *
                  *   COUNTER REGISTER AND THE $D070 BUFFER       *
```

```
                   *   SO THAT NO STEPS ARE MISSED WHILE           *
                   *   SEQUENCING MOTOR Y IN THE CLOCKWISE         *
                   *   DIRECTION.                                  *
                   *                                               *
                   **************************************************
                   *
                   *
FF6F A6   89 D044  MOTOD  LDA SEQY,X
FF73 B7   D070            STA $D070
FF76 30   1F              LEAX -1,X
FF78 BF   D067            STX NUMY
FF7B 8C   FFFF            CMPX #-1
FF7E 26   03              BNE NYAOK
FF80 BD   F724            JSR SETYA
FF83 39            NYAOK  RTS
                   *
                   *
                   **************************************************
                   *                                               *
                   *    SUBROUTINE MCONTA.                         *
                   *    FOR THE NUMBER OF STEPS TO BE TAKEN        *
                   *    BY MOTORS X AND Y > 10 , THIS ROUTINE      *
                   *    ENABLES THE MOTORS TO BE SEQIENCED         *
                   *    AT A RAMPING SPEED OF 15 STEPS/SEC.        *
                   *    AFTER FIRST FIVE STEPS AT CONSTANT         *
                   *    STEPPING RATE OF 2 STEPS/SEC. UNTIL        *
                   *    ONLY FIVE STEPS REMAINS.                   *
                   *                                               *
                   **************************************************
                   *
                   *
FF84 C1   05       MCONTA CMPB #5
FF86 22   09              BHI RMPA
FF88 108E 1770            LDY #6000
```

```
FF8C BD   F6D9            JSR DLY2
FF8F 20   07              BRA RMPC
FF91 108E 0BB8    RMPA    LDY #3000
FF95 BD   F6D9            JSR DLY2
FF98 39           RMPC    RTS
                  *
                  *
                  ***********************************************
                  *                                             *
                  *    SUBROUTINE  RATIO.                       *
                  *    THIS ROUTINE CALCULATES THE SLOPE OF     *
                  *    THE MICROELECTRODE TRAVEL IN X-Y PLANE   *
                  *    EITHER AS 1:Y OR AS X:1 SLOPE .          *
                  *                                             *
                  ***********************************************
                  *
                  *
                  ***********************************************
                  *                                             *
                  *    NOTE : The following subroutines        *
                  *           reside in EPROM 2                 *
                  *                                             *
                  ***********************************************
                  *
                  *
F6AC                      ORG $F6AC
F6AC C6   08      RATIO   LDB #8
F6AE F7   D080            STB CONT
F6B1 FC   D078            LDD MURTIO
F6B4 58           RTO     ASLB
F6B5 49                   ROLA
F6B6 B1   D074            CMPA MLRTIO
F6B9 25   04              BCS CHKCT
F6BB B0   D074            SUBA MLRTIO
```

```
F6BE 5C                    INCB
F6BF 7A    D080     CHKCT  DEC CONT
F6C2 26    F0              BNE RTO
F6C4 48                    LSLA
F6C5 B1    D074            CMPA MLRTIO
F6C8 25    01              BLO NOCHG
F6CA 5C                    INCB
F6CB 39             NOCHG  RTS
                    *
                    *
                    ****************************************************
                    *                                                  *
                    *    SUBROUTINE DELY4                              *
                    *                                                  *
                    ****************************************************
                    *
                    *
F6CC 108E 0064      DELY4  LDY #100
F6D0 31    3F       DLY4   LEAY -1,Y
F6D2 26    FC              BNE DLY4
F6D4 39                    RTS
                    *
                    *
                    ****************************************************
                    *                                                  *
                    *     SUBROUTINE  DELY2                            *
                    * THIS  ROUTINE  GIVES 2 STEP/SEC MOTOR SPEED.     *
                    *                                                  *
                    ****************************************************
                    *
                    *
F6D5 108E 3A98      DELY2  LDY #15000
F6D9 31    3F       DLY2   LEAY -1,Y
F6DB 26    FC              BNE DLY2
```

```
F6DD 39                   RTS
                   *
                   *
                   ****************************************************
                   *                                                  *
                   *  SUBROUTINE  MCOUNT                              *
                   *                                                  *
                   ****************************************************
                   *
                   *
F6DE 7C   D050     MCOUNT INC COUNTR          IS COUNT = 5
F6E1 F6   D050            LDB COUNTR
F6E4 C1   05              CMPB #5
F6E6 22   05              BHI  RMP            YES GO TO RAMP MODE
F6E8 BD   F6D5            JSR DELY2           NO  STAY IN CONSTANT MODE
F6EB 20   07              BRA  RMPB
F6ED 108E 1770     RMP    LDY #6000
F6F1 BD   F6D9            JSR DLY2
F6F4 39            RMPB   RTS
                   *
                   *
                   **************************************************
                   *                                                *
                   *     SUBROUTINE DISPL1                          *
                   *  THIS ROUTINE DISPLAYS DIGITS FROM DIGT1 TO    *
                   *  DIGT8.  THAT IS  X AND Y POSITIONS.           *
                   *                                                *
                   **************************************************
                   *
                   *
F6F5 BD   F743     DISPL1 JSR DSPXY     TAKE MODE LINE HIGH DISPLAY 1
F6F8 8E   0000            LDX #0
F6FB C6   08              LDB #8
F6FD A6   89 D000  NXDGT1 LDA DIGT1,X          DISPLAY DIGITS 1 -8
```

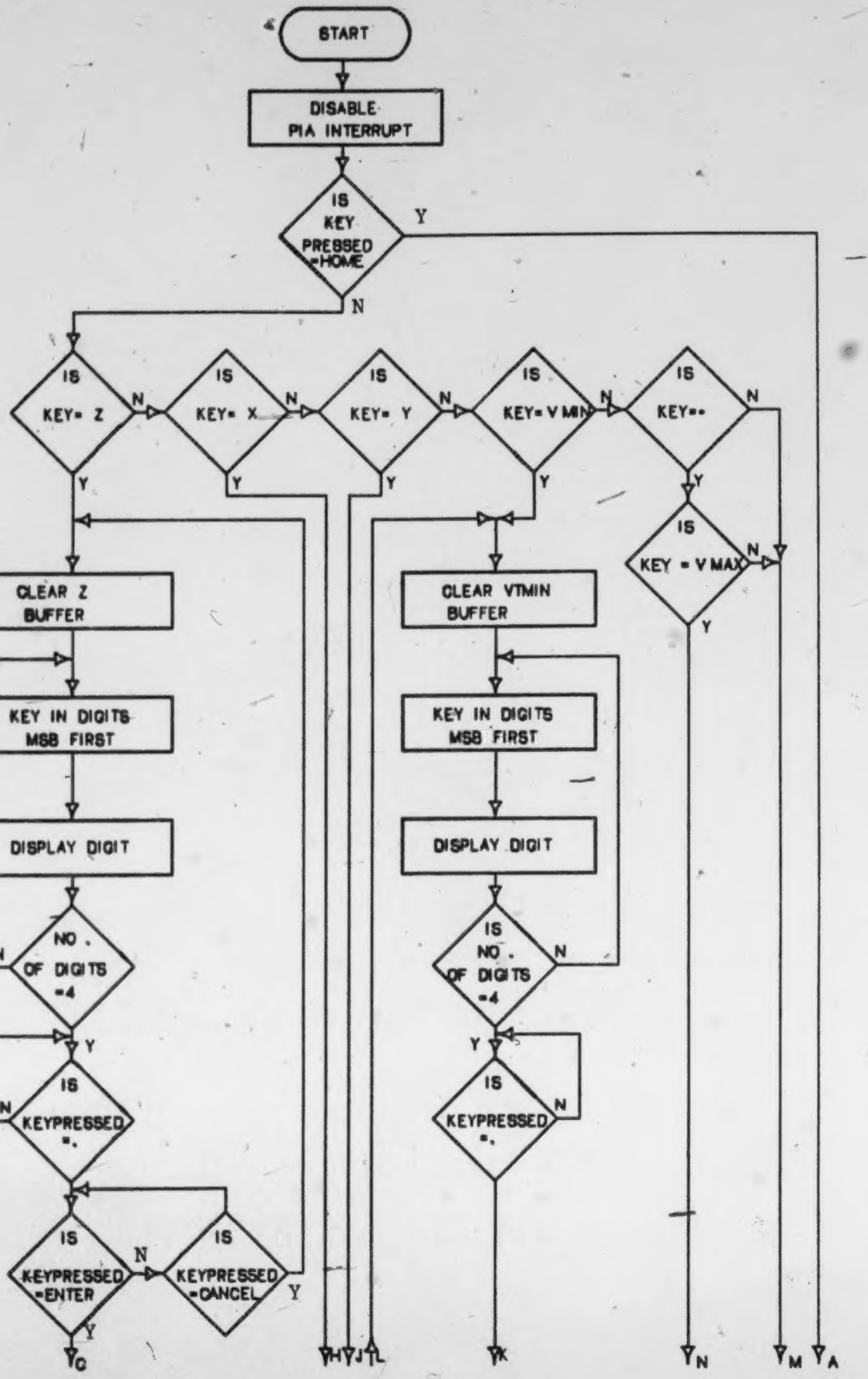
```
F701 B7    C000            STA DISP1
F704 30    01              LEAX 1,X
F706 5A                    DECB
F707 26    F4              BNE NXDGT1
F709 39                    RTS
                   *
                   *
                   **************************************************
                   *                                                *
                   *     SUBROUTINE  DISPL2                         *
                   *   THIS ROUTINE DISPLAYS DIGITS FROM DIGT9 TO   *
                   *   DIGT20. THAT IS Z AND VTH VALUES.            *
                   *                                                *
                   **************************************************
                   *
                   *
F70A BD    F756     DISPL2 JSR DSPZV
F70D 8E    0000     NXDGTZ LDX #0
F710 C6    08              LDB #8
F712 A6    89 D008  NXDGT2 LDA DIGT9,X
F716 B7    C008            STA DISP2
F719 30    01              LEAX 1,X
F71B 5A                    DECB
F71C 26    F4              BNE NXDGT2
F71E 39                    RTS
                   *
                   *
                   **************************************************
                   *                                                *
                   *    SUBROUTINE SETYA  AND SETYB.                *
                   *    THIS ROUTINE UPDATES THE SEQUENCE           *
                   *    COUNTER Y (NUMY) WITH "0" FOR COUNTER       *
                   *    CLOCKWISE ROTATION AND WITH "3" FOR         *
                   *    CLOCKWISE ROTATION.                         *
                   *                                                 *
                   ***************************************************
                   *
                   *
F71F 8E   0000     SETYB  LDX #0
F722 20   03              BRA SETSTY
F724 8E   0003     SETYA  LDX #3
F727 BF   D067     SETSTY STX NUMY
F72A 39                   RTS
                   *
                   *
                   ***************************************************
                   *                                                 *
                   *    SUBROUTINE SETXA AND SETXB                   *
                   *    THIS ROUTINE UPDATES THE SEQUENCE            *
                   *    COUNTER X (NUMX) WITH "0" FOR COUNTER        *
                   *    CLOCKWISE ROTATION AND WITH "3" FOR          *
                   *    CLOCKWISE ROTATION.                          *
                   *                                                 *
                   ***************************************************
                   *
                   *
F72B 8E   0000     SETXB  LDX #0
F72E 20   03              BRA SETSTX
F730 8E   0003     SETXA  LDX #3
F733 BF   D069     SETSTX STX NUMX
F736 39                   RTS
                   *
                   *
                   ***************************************************
                   *                                                 *
                   *     SUBROUTINE SETZA AND SETZB                  *
                   *     THIS ROUTINE UPDATES THE SEQUENCE           *
                   *     COUNTER Z (NUMZ) WITH "0" FOR COUNTER       *
```

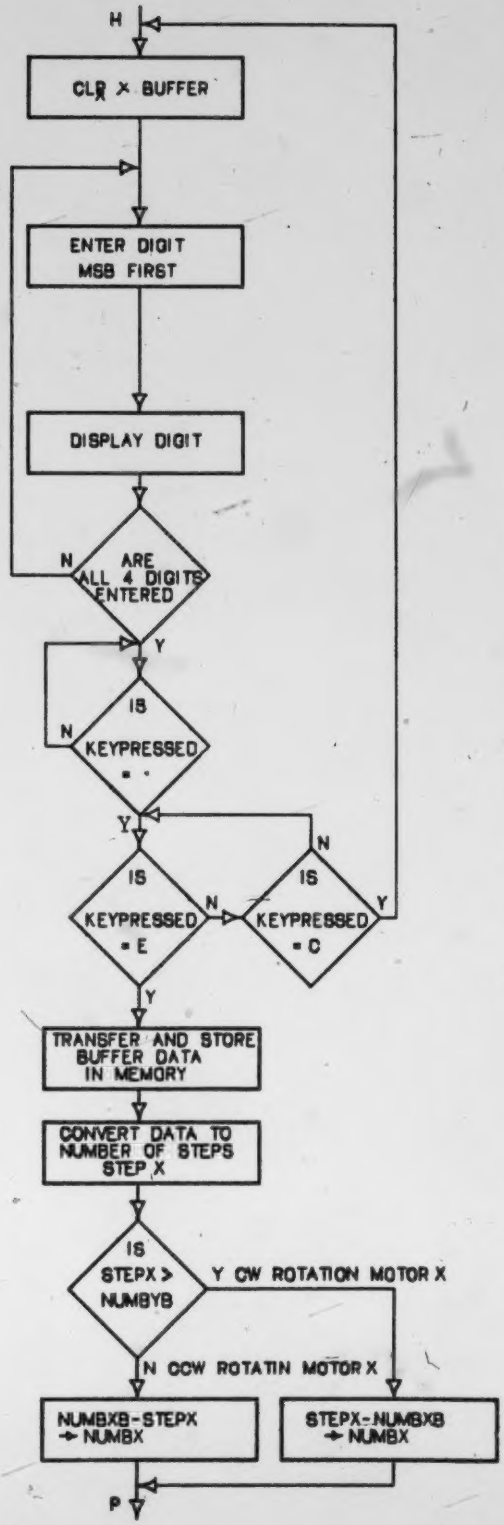
```
                    *     CLOCKWISE ROTATION AND WITH "3" FOR      *
                    *     CLOCKWISE ROTATION.                      *
                    *                                              *
                    ************************************************
                    *
                    *
F737 8E   0000      SETZB   LDX #0
F73A 20   03                BRA SETSTZ
F73C 8E   0003      SETZA   LDX #3
F73F BF   D065      SETSTZ  STX NUMZ
F742 39                     RTS
                    *
                    *
                    ************************************************
                    *                                              *
                    *     SUBROUTINE DSPXY                         *
                    *     THIS ROUTINE SELECTS THE XY INTERSIL     *
                    *     DISPLAY CHIP AND SETS THE MODE TO        *
                    *     HEXADECIMAL DECODE.  THE CHIP IS         *
                    *     CONTROLLED VIA PIA2 PORTB LINE PB6.      *
                    *                                              *
                    ************************************************
                    *
                    *
F743 B6   D072      DSPXY   LDA $D072
F746 8A   40                ORA #%01000000
F748 B7   9002              STA PIA2DB
F74B C6   D0                LDB #%11010000
F74D F7   C000              STB DISP1
F750 84   BF                ANDA #%10111111
F752 B7   9002              STA PIA2DB
F755 39                     RTS
                    *
                    *
```

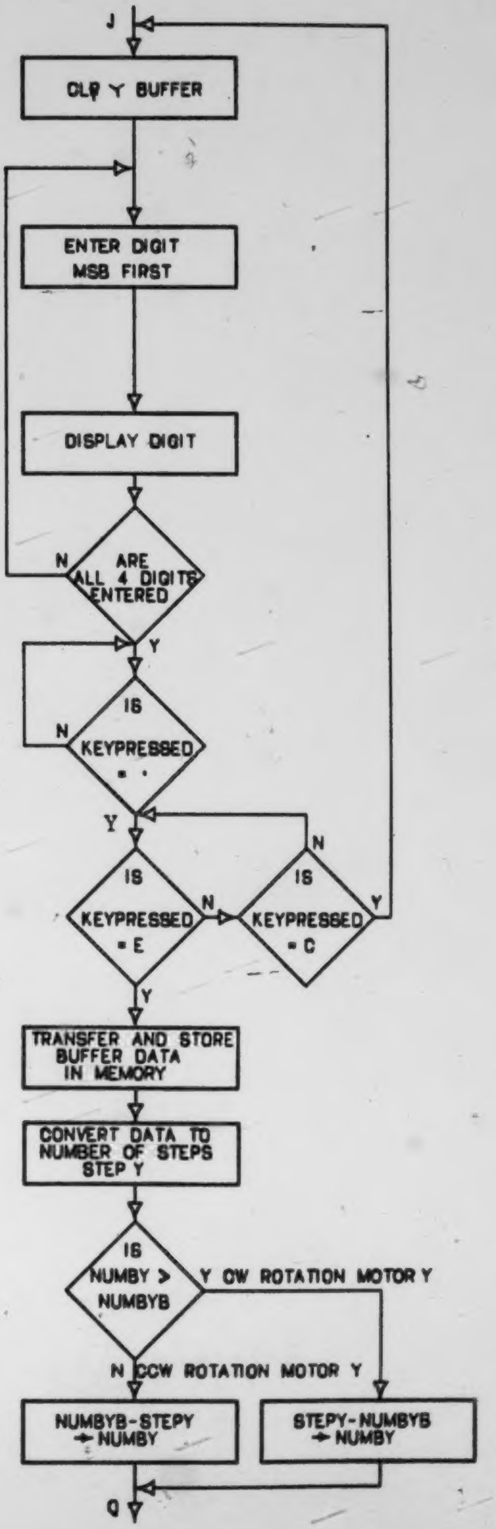
```
                     ********************************************
                     *                                          *
                     *     SUBROUTINE DSPZV                     *
                     *     THIS ROUTINE SELECTS THE ZV INTERSIL *
                     *     DISPLAY CHIP AND SETS THE MODE TO    *
                     *     HEXADECIMAL DECODE.  THE CHIP IS     *
                     *     CONTROLLED VIA PIA2 PORTB LINE PB7.  *
                     *                                          *
                     ********************************************
                     *
                     *
F756 B6   D072       DSPZV  LDA $D072
F759 8A   80                ORA #%10000000
F75B B7   9002              STA PIA2DB
F75E C6   D0                LDB #%11010000
F760 F7   C008              STB DISP2
F763 84   7F                ANDA #%01111111
F765 B7   9002              STA PIA2DB
F768 39                     RTS
                     *
                     *
                     ********************************************
                     *                                          *
                     *   SUBROUTINE  MOTOA.                     *
                     *   THIS ROUTINE IS USED TO UPDATE SEQ. X  *
                     *   COUNTER REGISTER AND THE $D071 BUFFER  *
                     *   SO THAT NO STEPS ARE MISSED WHILE      *
                     *   SEQUENCING MOTOR X IN CLOCKWISE        *
                     *   DIRECTION.                             *
                     *                                          *
                     ********************************************
                     *
                     *
F7C0                        ORG $F7C0
```

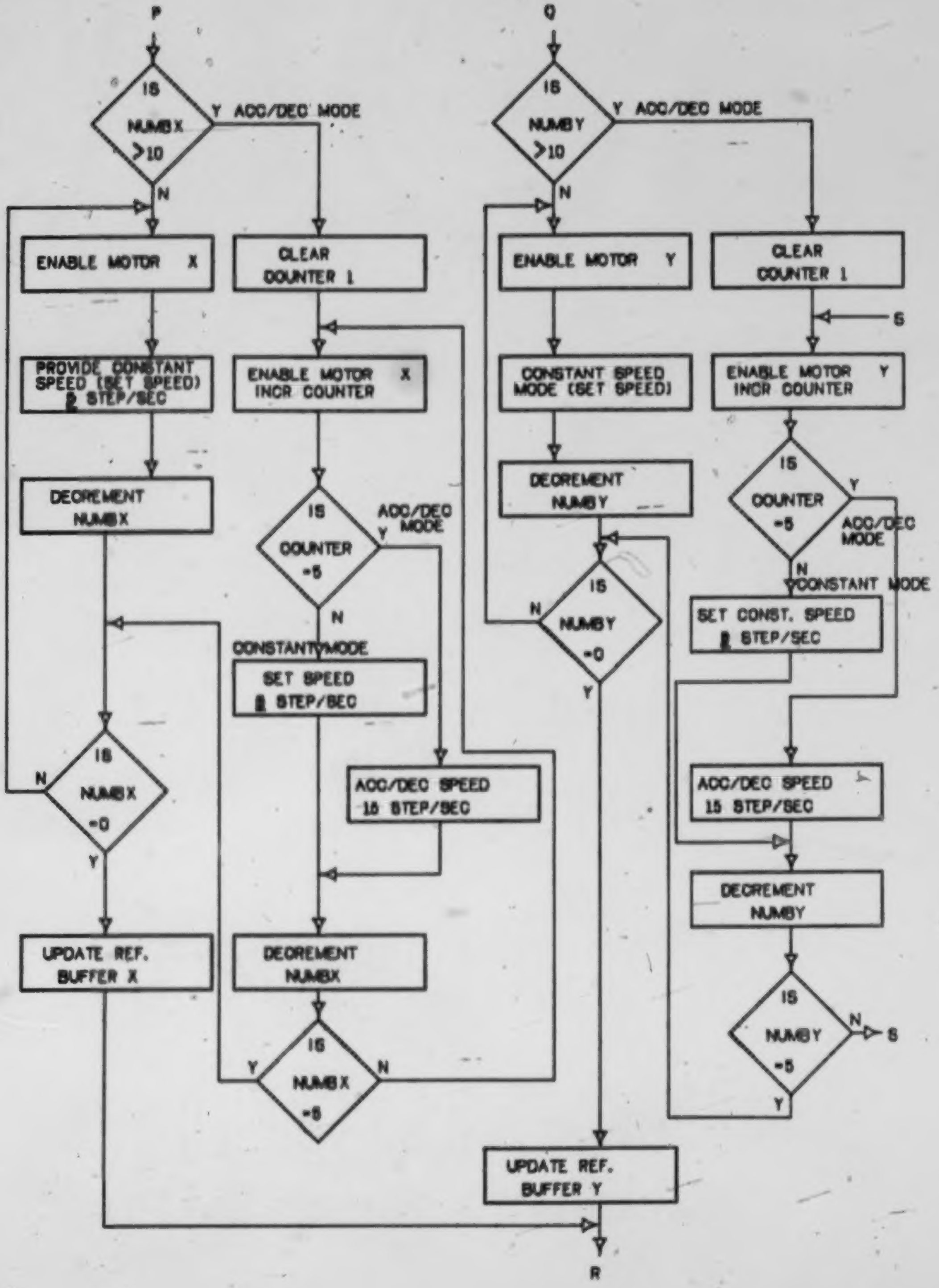
```
F7C0 A6   89 D040   MOTOA  LDA SEQXZ,X
F7C4 B7   D071             STA $D071
F7C7 30   1F               LEAX -1,X
F7C9 BF   D069             STX NUMX
F7CC 8C   FFFF             CMPX #-1
F7CF 26   03               BNE NXAOK
F7D1 BD   F730             JSR SETXA
F7D4 39             NXAOK  RTS
                    *
                    *
                    **************************************************
                    *                                                *
                    *   SUBROUTINE MOTOB.                            *
                    *   THIS ROUTINE IS USED TO UPDATE SEQ. X        *
                    *   COUNTER REGISTER AND THE $D071 BUFFER        *
                    *   SO THAT NO STEP IS MISSED WHILE              *
                    *   SEQUENCING MOTOR X IN THE COUNTER CLOCK      *
                    *   WISE DIRECTION.                              *
                    *                                                *
                    **************************************************
                    *
                    *
F7D5 A6   89 D040   MOTOB  LDA SEQXZ,X
F7D9 B7   D071             STA $D071
F7DC 30   01               LEAX 1,X
F7DE BF   D069             STX NUMX
F7E1 8C   0004             CMPX #4
F7E4 26   03               BNE NXBOK
F7E6 BD   F72B             JSR SETXB
F7E9 39             NXBOK  RTS
                    *
                    *
FFFE                       ORG $FFFE
FFFE F800                  FDB RESET    RESET VECTOR
```

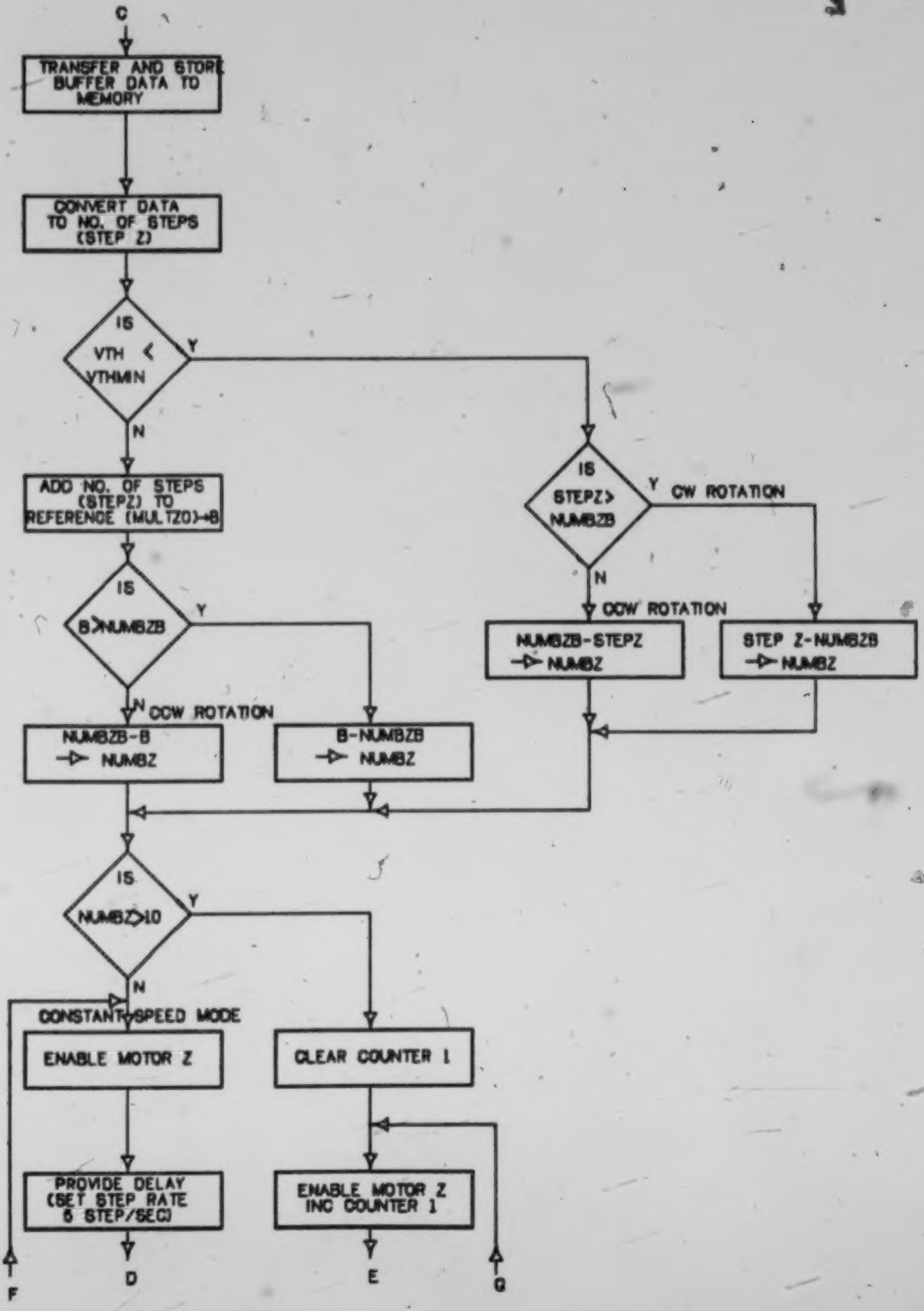
```
                   *
                   *
FFF8                     ORG $FFF8
FFF8 F000                FDB INTRPT   INTERRUPT VECTOR
                   *
                   *
                   *
                   *
                   *********************************************
                   *                                           *
                   *        END OF EPROM 1 PROGRAMME           *
                   *                                           *
                   *********************************************
                   *
                   *
0000                     END
*
```

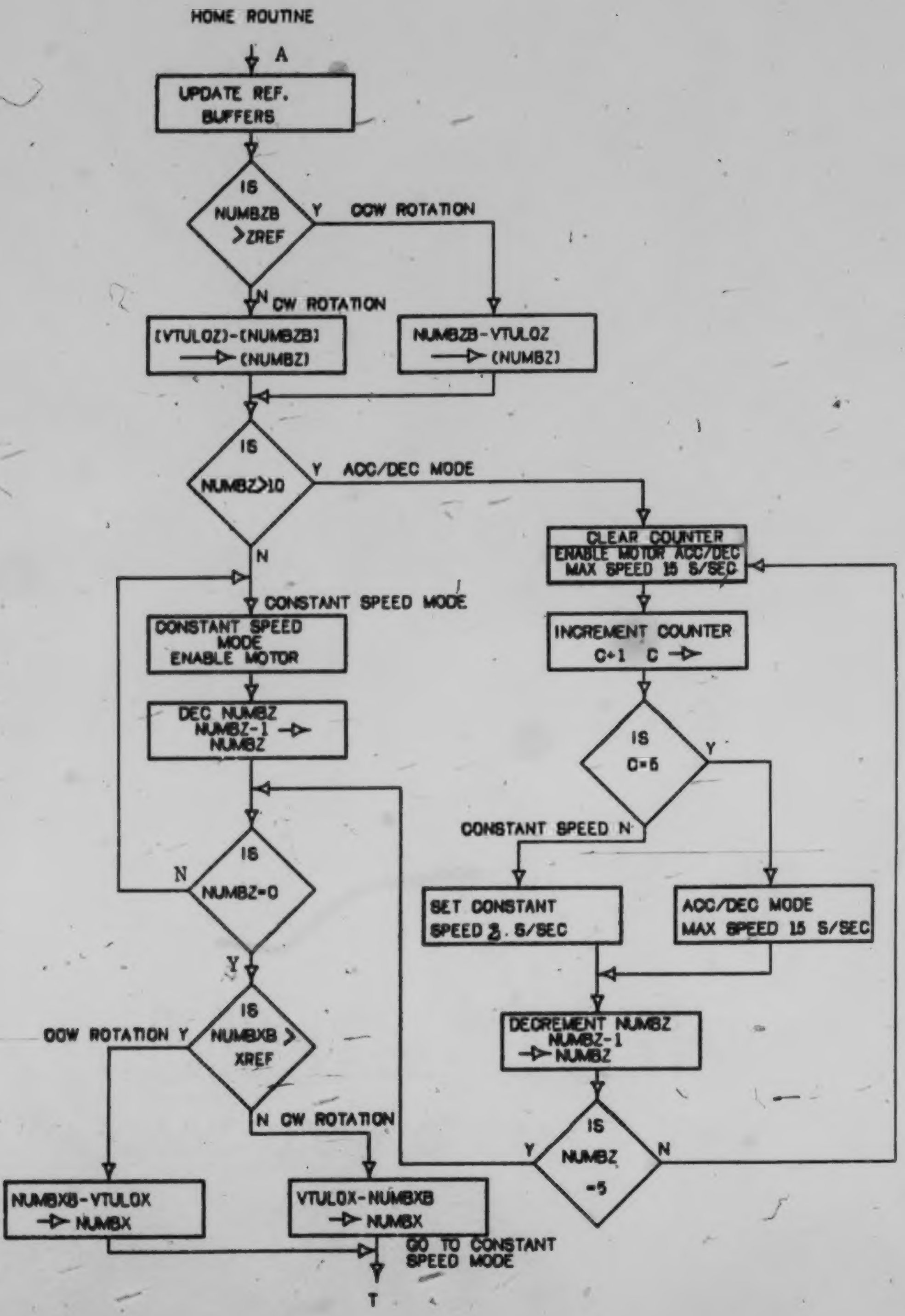

START
DISABLE PIA INTERRUPT
IS KEY PRESSED =HOME
Y
N
IS KEY= Z
N
IS KEY= X
N
IS KEY= Y
N
IS KEY=VMIN
N
IS KEY=.
N
Y
Y
Y
Y
Y
IS KEY = VMAX
N
Y
CLEAR Z BUFFER
KEY IN DIGITS MSB FIRST
DISPLAY DIGIT
NO. OF DIGITS =4
N
Y
IS KEYPRESSED =.
N
IS KEYPRESSED =ENTER
N
IS KEYPRESSED =CANCEL
Y
Y
C
H
J
L
CLEAR VTMIN BUFFER
KEY IN DIGITS MSB FIRST
DISPLAY DIGIT
IS NO. OF DIGITS =4
N
Y
IS KEYPRESSED =.
N
K
N
M
A

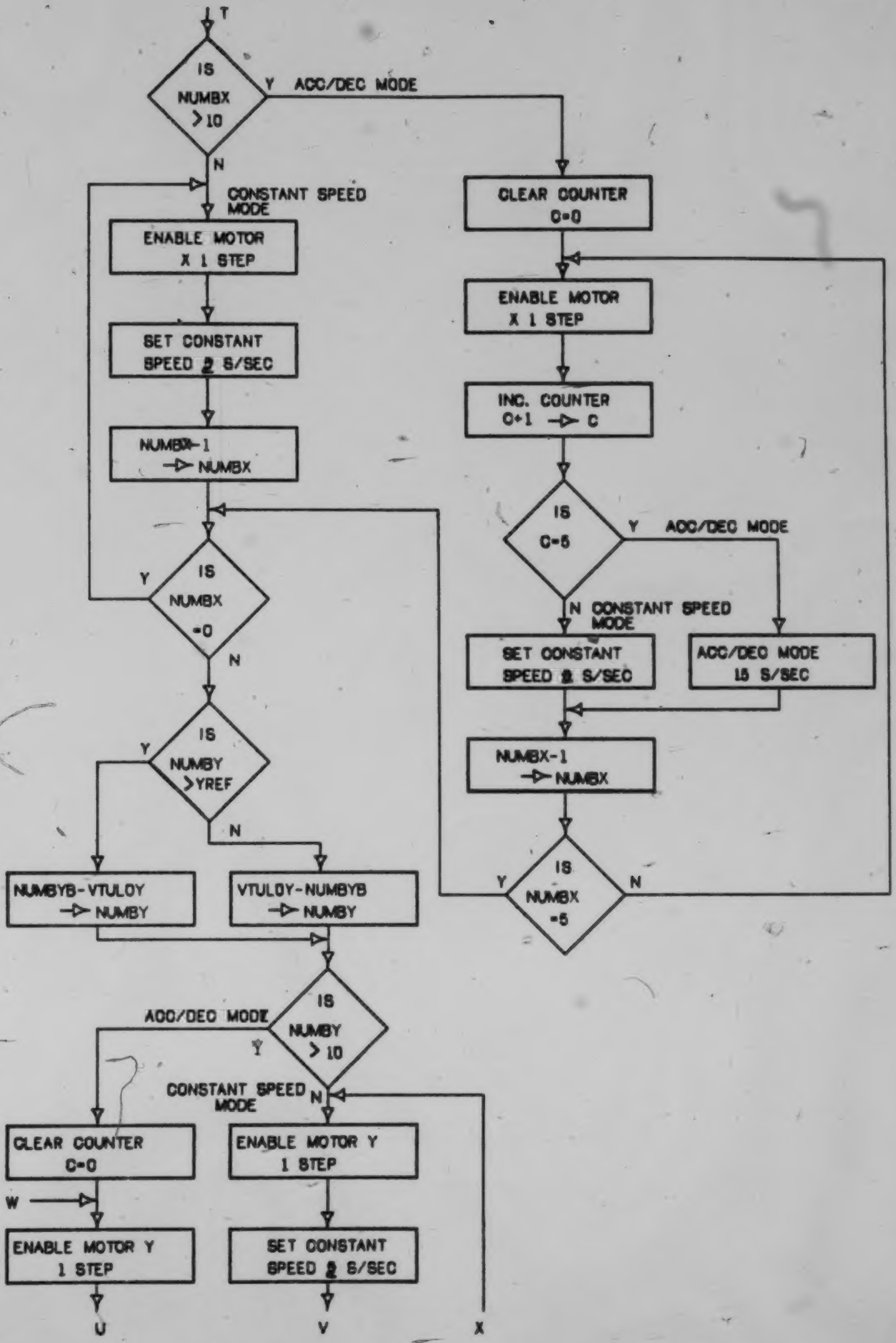

H
CLR X BUFFER
ENTER DIGIT MSB FIRST
DISPLAY DIGIT
ARE ALL 4 DIGITS ENTERED
N
Y
IS KEYPRESSED = ·
N
Y
IS KEYPRESSED = E
N
IS KEYPRESSED = C
N
Y
Y
TRANSFER AND STORE BUFFER DATA IN MEMORY
CONVERT DATA TO NUMBER OF STEPS STEP X
IS STEPX > NUMBYB
Y CW ROTATION MOTOR X
N CCW ROTATIN MOTOR X
NUMBXB-STEPX → NUMBX
STEPX-NUMBXB → NUMBX
P

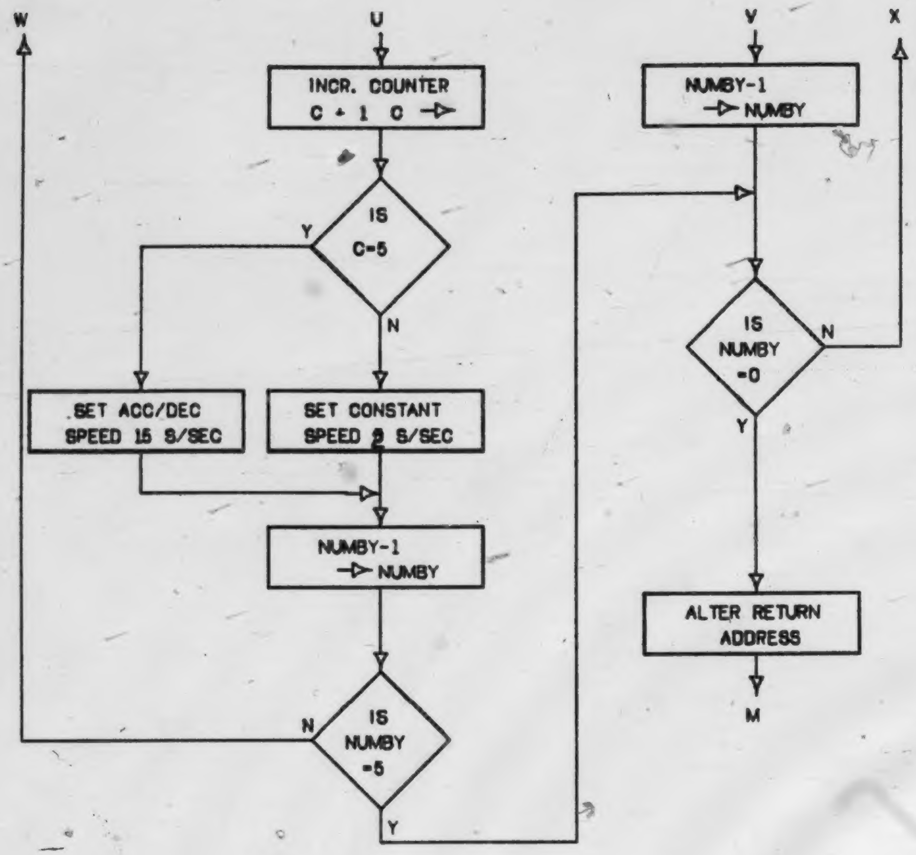

J
CLR Y BUFFER
ENTER DIGIT MSB FIRST
DISPLAY DIGIT
ARE ALL 4 DIGITS ENTERED
N
Y
IS KEYPRESSED = ·
N
Y
IS KEYPRESSED = E
N
IS KEYPRESSED = C
N
Y
Y
TRANSFER AND STORE BUFFER DATA IN MEMORY
CONVERT DATA TO NUMBER OF STEPS STEP Y
IS NUMBY > NUMBYB
Y CW ROTATION MOTOR Y
N CCW ROTATION MOTOR Y
NUMBYB-STEPY → NUMBY
STEPY-NUMBYB → NUMBY
Q

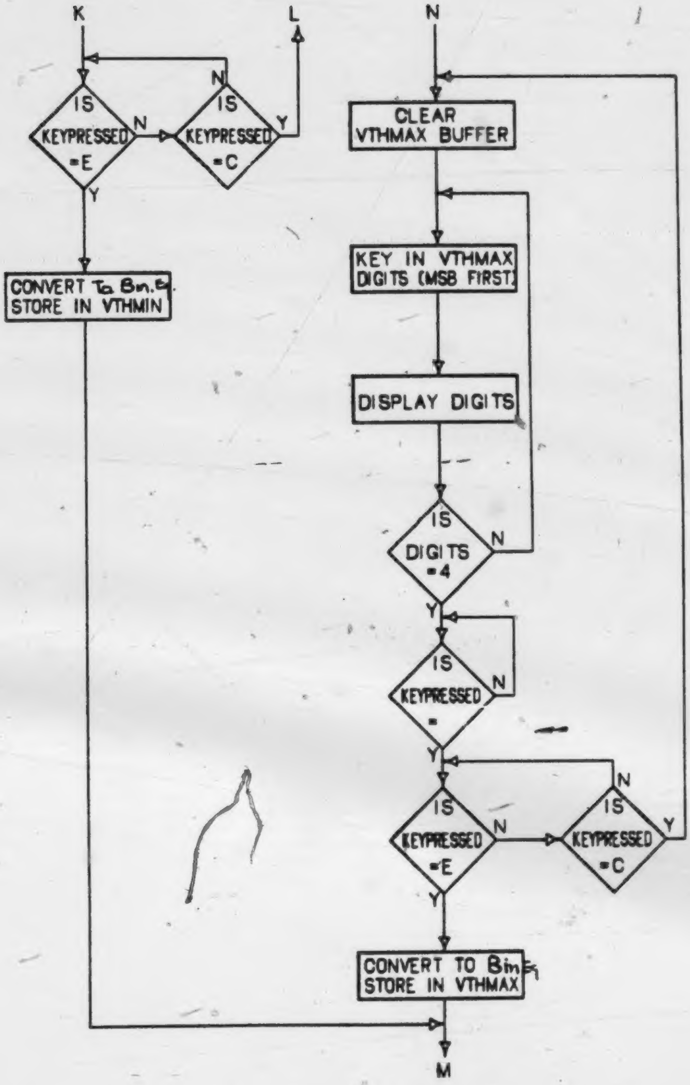

P
IS NUMBX >10
Y ACC/DEC MODE
N
ENABLE MOTOR X
CLEAR COUNTER 1
PROVIDE CONSTANT SPEED (SET SPEED) 2 STEP/SEC
ENABLE MOTOR X INCR COUNTER
DECREMENT NUMBX
IS COUNTER =5
Y ACC/DEC MODE
N
CONSTANT MODE
SET SPEED 2 STEP/SEC
ACC/DEC SPEED 15 STEP/SEC
IS NUMBX =0
N
Y
UPDATE REF. BUFFER X
DECREMENT NUMBX
IS NUMBX =5
Y
N
Q
IS NUMBY >10
Y ACC/DEC MODE
N
ENABLE MOTOR Y
CLEAR COUNTER 1
S
CONSTANT SPEED MODE (SET SPEED)
ENABLE MOTOR Y INCR COUNTER
DECREMENT NUMBY
IS COUNTER =5
Y ACC/DEC MODE
N CONSTANT MODE
SET CONST. SPEED 2 STEP/SEC
IS NUMBY =0
N
Y
ACC/DEC SPEED 15 STEP/SEC
DECREMENT NUMBY
IS NUMBY =5
N
S
Y
UPDATE REF. BUFFER Y
R


C
TRANSFER AND STORE BUFFER DATA TO MEMORY
CONVERT DATA TO NO. OF STEPS (STEP Z)
IS VTH < VTHMIN
Y
N
ADD NO. OF STEPS (STEPZ) TO REFERENCE (MULTZO)→B
IS B>NUMBZB
Y
N
CCW ROTATION
NUMBZB-B → NUMBZ
B-NUMBZB → NUMBZ
IS STEPZ> NUMBZB
Y
CW ROTATION
N
CCW ROTATION
NUMBZB-STEPZ → NUMBZ
STEP Z-NUMBZB → NUMBZ
IS NUMBZ>10
Y
N
CONSTANT SPEED MODE
ENABLE MOTOR Z
PROVIDE DELAY (SET STEP RATE 5 STEP/SEC)
CLEAR COUNTER 1
ENABLE MOTOR Z INC COUNTER 1
F
D
E
G


HOME ROUTINE
A
UPDATE REF. BUFFERS
IS NUMBZB >ZREF
Y
CCW ROTATION
N
CW ROTATION
(VTULOZ)-(NUMBZB) ⟶ (NUMBZ)
NUMBZB-VTULOZ ⟶ (NUMBZ)
IS NUMBZ>10
Y
ACC/DEC MODE
N
CONSTANT SPEED MODE
CONSTANT SPEED MODE ENABLE MOTOR
DEC NUMBZ NUMBZ-1 ⟶ NUMBZ
IS NUMBZ=0
N
Y
IS NUMBXB > XREF
CCW ROTATION Y
N CW ROTATION
NUMBXB-VTULOX ⟶ NUMBX
VTULOX-NUMBXB ⟶ NUMBX
GO TO CONSTANT SPEED MODE
T
CLEAR COUNTER ENABLE MOTOR ACC/DEC MAX SPEED 15 S/SEC
INCREMENT COUNTER C+1 C ⟶
IS C=5
Y
CONSTANT SPEED N
SET CONSTANT SPEED 2. S/SEC
ACC/DEC MODE MAX SPEED 15 S/SEC
DECREMENT NUMBZ NUMBZ-1 ⟶ NUMBZ
IS NUMBZ =5
Y
N


T
IS NUMBX >10
Y ACC/DEC MODE
N
CONSTANT SPEED MODE
ENABLE MOTOR X 1 STEP
SET CONSTANT SPEED 2 S/SEC
NUMBX-1 → NUMBX
IS NUMBX =0
Y
N
IS NUMBY >YREF
Y
N
NUMBYB-VTULOY → NUMBY
VTULOY-NUMBYB → NUMBY
IS NUMBY > 10
ACC/DEC MODE
Y
CONSTANT SPEED MODE
N
CLEAR COUNTER C=0
W
ENABLE MOTOR Y 1 STEP
U
ENABLE MOTOR Y 1 STEP
SET CONSTANT SPEED 2 S/SEC
V
X
CLEAR COUNTER C=0
ENABLE MOTOR X 1 STEP
INC. COUNTER C+1 → C
IS C=5
Y ACC/DEC MODE
N CONSTANT SPEED MODE
SET CONSTANT SPEED 2 S/SEC
ACC/DEC MODE 15 S/SEC
NUMBX-1 → NUMBX
IS NUMBX =5
Y
N


W
U
V
X
INCR. COUNTER
C + 1 C ⊳
IS
C=5
Y
N
.SET ACC/DEC
SPEED 15 S/SEC
SET CONSTANT
SPEED 5 S/SEC
NUMBY-1
⊳ NUMBY
IS
NUMBY
=5
N
Y
NUMBY-1
⊳ NUMBY
IS
NUMBY
=0
N
Y
ALTER RETURN
ADDRESS
M


K
L
N
IS KEYPRESSED =E
N
Y
IS KEYPRESSED =C
N
Y
CONVERT To Bin. & STORE IN VTHMIN
CLEAR VTHMAX BUFFER
KEY IN VTHMAX DIGITS (MSB FIRST)
DISPLAY DIGITS
IS DIGITS =4
N
Y
IS KEYPRESSED =
N
Y
IS KEYPRESSED =E
N
Y
IS KEYPRESSED =C
N
Y
CONVERT TO Bin & STORE IN VTHMAX
M

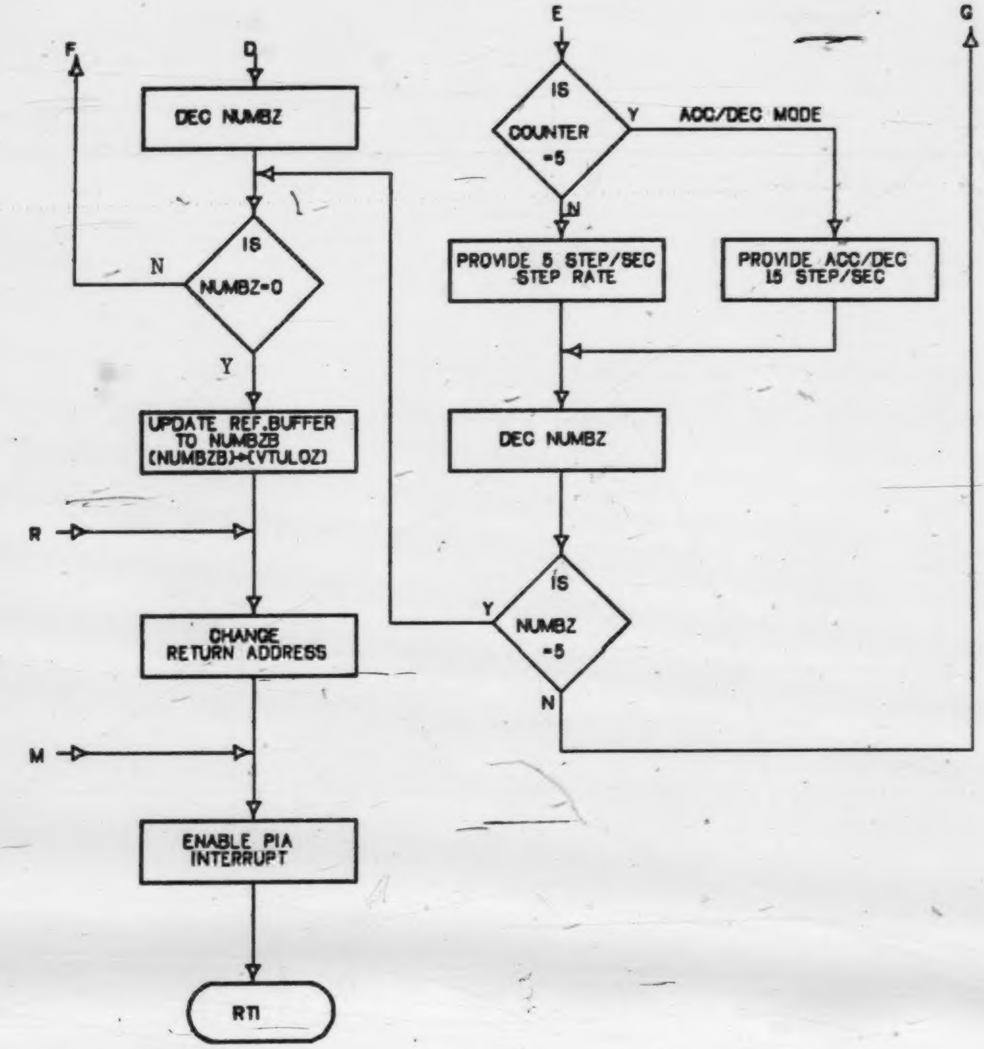

F
D
DEC NUMBZ
IS
NUMBZ=0
N
Y
UPDATE REF.BUFFER TO NUMBZB (NUMBZB)→(VTULOZ)
R
CHANGE RETURN ADDRESS
M
ENABLE PIA INTERRUPT
RTI
E
G
IS
COUNTER
=5
Y
ACC/DEC MODE
N
PROVIDE 5 STEP/SEC STEP RATE
PROVIDE ACC/DEC 15 STEP/SEC
DEC NUMBZ
IS
NUMBZ
=5
Y
N

Figure B.2 Interrupt Routine Flow Chart

INTERRUPT ROUTINE

```
OBJECT CODE        SOURCE STATEMENT

                   *************************************************
                   *                                               *
                   *   THE SYSTEM IS INTRUPTED WHEN EVER THE KEY IS*
                   *   IS PRESSED. THIS ROUTINE ENABLES THE SYSTEM *
                   *   TO GO TO "HOME" POSITION , ENTER ALL        *
                   *   VARIABLE PARAMETERS (X , Y , Z DISPLACEMENT *
                   *   & THRESHOLD VOLTS ). THE ROUTINE ALSO HAS   *
                   *   THE FACILITY TO CLEAR PARAMETERS IF AN      *
                   *   ERROR IS MADE IN ENTRY. ON RETURNING FROM   *
                   *   KEYBOARD MODE THE SYSTEM EITHER GOES INTO   *
                   *   "HOME" MODE OR "STANDBY" MODE DEPENDING     *
                   *   ON THE KEYBOARD ACTION REQUESTED.  IF ONLY  *
                   *   THE THRESHOLD VOLTAGE ENTRY IS MADE THEN    *
                   *   THE SYSTEM RETURNS TO THE MAIN PROGRAMME    *
                   *   JUST BEFORE INTERRUPT.                      *
                   *                                               *
                   *************************************************
                   *
                   *
F000                       ORG INTRPT
F000 B6   8001             LDA PIA1CA
F003 84   FE               ANDA #%11111110      DISABLE PIA INT.
F005 B7   8001             STA PIA1CA
F008 B6   8000             LDA PIA1DA
F00B 86   A0               LDA #%10100000
F00D B7   8000             STA PIA1DA
F010 BD   F6A9     KFWAIT  JSR READK
F013 81   0F               CMPA #$0F
```

```
F015 1027 03C8             LBEQ HOME      IS KEY PRESSED YES GO TO HOME
F019 81   0C               CMPA #$0C      IS KEY PRESSED = Z
F01B 27   2A               BEQ INPUTZ     YES GO TO Z INPUT
F01D 81   0A               CMPA #$0A      IS KEY PRESSED = TO X
F01F 1027 0155             LBEQ INPUTX    YES GO TO X ENTRY
F023 81   0B               CMPA #$0B      IS KEY PRESSED = Y
F025 1027 0258             LBEQ INPUTY    YES GO TO Y ENTRY
F029 81   0D               CMPA #$0D      IS KEY PRESSED = VTHMIN
F02B 1027 0358             LBEQ INPVTM    YES GO TO VTHMIN ENTRY
F02F 81   0E               CMPA #$0E      IS KEY PRESSED = FUNCTION
F031 1026 0138             LBNE RTNVT     NO  RETURN
                    *
F035 BD   F6A9      KWAIT1 JSR READK
F038 81   0C               CMPA #$0C
F03A 1027 011A             LBEQ GO
F03E 81   0F               CMPA #$0F
F040 1027 011B             LBEQ CONTUE
F044 16   012B             LBRA RTNVT1
                    *
                    *
                    ***********************************************
                    *                                             *
                    *   Z PENETRATION ENTRY. IN THIS ROUTINE THE  *
                    *   REQUIRED Z DISPLACEMENT OF THE MANIPULATOR*
                    *   IS ENTERED VIA KEYBOARD.                  *
                    *                                             *
                    ***********************************************
                    *
                    *
                    ***********************************************
                    *                                             *
                    *   INITIALISE Z DISPLAYS TO READ ALL ZERO    *
                    *                                             *
                    ***********************************************
```

```
                   *
                   *
F047 4F            INPUTZ CLRA
F048 C6   04              LDB #4
F04A 8E   0000            LDX #0
F04D A7   89 D018  CONTZ  STA BUFF9,X        CLEAR Z BUFFER
F051 30   01              LEAX 1,X
F053 5A                   DECB
F054 26   F7              BNE CONTZ
F056 BD   F675            JSR DISPZV          CLEAR Z DISPLAY
F059 C6   04              LDB #4
F05B 8E   0003            LDX #3
                   *
                   *
                   ************************************************
                   *                                              *
                   *   ENTER Z DISPLACEMENT IN MICRONS WITH M.S.D.*
                   *   FIRST AND DISPLAY DIGITS AS ENTERED. IF ANY*
                   *   ERROR IS MADE IN ENTRY THE ENTRY CAN BE    *
                   *   CLEARED AND REENTERED AGAIN. IF NO ERROR   *
                   *   IS MADE THEN THE DIGITS ARE TRANSFERRED    *
                   *   FOR STORAGE AND FURTHER CALCULATION.       *
                   *                                              *
                   ************************************************
                   *
                   *
F05E BD   F6A9     KZWAIT JSR READK
F061 A7   89 D018         STA BUFF9,X
F065 30   1F              LEAX -1,X
F067 BD   F675            JSR DISPZV
F06A 5A                   DECB               ARE ALL 4 DIGITS ENTERED
F06B 26   F1              BNE KZWAIT         NO CONTINUE
                   *
F06D BD   F6A9     FZWAIT JSR READK
```

```
F070 81    0E                CMPA #$0E         IS KEY PRESSED = FUNCTION
F072 26    F9                BNE FZWAIT        NO CONTINUE SCAN
                   *
F074 BD    F6A9    EZWAIT JSR READK
F077 81    0A                CMPA #$0A         IS KEY PRESSED = ENTER
F079 27    06                BEQ ENTERZ
F07B 81    0B                CMPA #$0B         IS THE KEY PRESSED = CANCEL
F07D 27    C8                BEQ INPUTZ        YES CLEAR DISP. & ENTER
                   *                           DIGITS AGAIN
F07F 20    F3                BRA EZWAIT        ENTER DIGITS AGAIN
                   *
F081 C6    04      ENTERZ LDB #4
F083 8E    0000             LDX #0
F086 A6    89 D018 TRANSZ LDA BUFF9,X       TRANSFER DATA FROM BUFFER TO
F08A A7    89 D008          STA DIGT9,X        DIGIT 9 TO DIGIT C
F08E 30    01               LEAX 1,X
F090 5A                     DECB               ARE ALL DIGITS TRANSFERED
F091 26    F3               BNE TRANSZ         NO CONTINUE
                   *
F093 BD    F712             JSR DISPL2        DISPLAY Z AND VTH
                   *
                   *
                   ***********************************************
                   *                                             *
                   *  CONVERT DISPLACEMENT TO NO. OF STEPS AND   *
                   *  STORE IN NUBBZ. CALCULATE THE DIRECTION    *
                   *  (C.F. PRESENT NUMBER > /L.T NUMBZB. IF     *
                   *   LESS THEN CCW ,IF > THEN CW ROTATION.     *
                   *                                             *
                   ***********************************************
                   *
                   *
F096 8E    0009             LDX #$09
F099 108E  0008             LDY #$08
```

```
F09D BD   F625          JSR RCONVT
F0A0 F6   D03F          LDB COUNT
F0A3 F7   D055          STB STEPZ
F0A6 F1   D034          CMPB VTUL0Z
F0A9 22   4F            BHI CONZF      IF > GIVE CW ROTATION
F0AB F7   D055          STB STEPZ
F0AE B6   D034          LDA VTUL0Z
F0B1 B0   D055          SUBA STEPZ
F0B4 4C                 INCA
F0B5 B7   D028          STA NUMBZ
F0B8 F6   D028   ZMCCW  LDB NUMBZ
F0BB C1   0A            CMPB #10
F0BD 22   1C            BHI KRMPZR
F0BF BE   D065   CONTZR LDX NUMZ
F0C2 BD   F7AF   STZCCW JSR SEQZKC          ENABLE STEPPER MOTOR Z
F0C5 7A   D028          DEC NUMBZ
F0C8 1027 0075          LBEQ RTNZ
F0CC 30   01     CSTZR  LEAX 1,X
F0CE BF   D065          STX NUMZ
F0D1 8C   0004          CMPX #4
F0D4 26   EC            BNE STZCCW
F0D6 BD   F73F          JSR SETZB
F0D9 20   E4            BRA CONTZR
F0DB 7F   D050   KRMPZR CLR COUNTR
F0DE BE   D065   KCNTZR LDX NUMZ
F0E1 BD   F7BA   KSZCCW JSR SEQZKR
F0E4 F6   D028          LDB NUMBZ
F0E7 C1   05            CMPB #5
F0E9 27   E1            BEQ CSTZR
F0EB 30   01            LEAX 1,X
F0ED BF   D065          STX NUMZ
F0F0 8C   0004          CMPX #4
F0F3 26   EC            BNE KSZCCW
F0F5 BD   F73F          JSR SETZB
```

```
F0F8 20   E4              BRA KCNTZR
                    *
F0FA F0   D034      CONZF  SUBB VTUL0Z
F0FD 5C                    INCB
F0FE F7   D028             STB NUMBZ
F101 F6   D028      ZMCW   LDB NUMBZ
F104 C1   0A               CMPB #10
F106 22   1A               BHI KRMPZF
F108 BE   D065      CONTZF LDX NUMZ
F10B BD   F7AF      STZCW  JSR SEQZKC       ENABLE STEPPER MOTOR Z
F10E 7A   D028             DEC NUMBZ          IS NO. OF STEPS = 0
F111 27   2E               BEQ RTNZ           NO CONTINUE SEQUENCE
F113 30   1F        CSTZF  LEAX -1,X
F115 BF   D065             STX NUMZ
F118 8C   FFFF             CMPX #-1
F11B 26   EE               BNE STZCW
F11D BD   F744             JSR SETZA
F120 20   E6               BRA CONTZF
F122 7F   D050      KRMPZF CLR COUNTR
F125 BE   D065      KCNTZF LDX NUMZ
F128 BD   F7BA      KSZCW  JSR SEQZKR
F12B F6   D028             LDB NUMBZ
F12E C1   05               CMPB #5
F130 27   E1               BEQ CSTZF
F132 30   1F               LEAX -1,X
F134 BF   D065             STX NUMZ
F137 8C   FFFF             CMPX #-1
F13A 26   EC               BNE KSZCW
F13C BD   F744             JSR SETZA
F13F 20   E4               BRA KCNTZF
                    *
                    *
F141 B6   D055      RTNZ   LDA STEPZ      RESTORE BUFFER TO INITIAL VALUE
F144 B7   D034             STA VTUL0Z
```

```
F147 B7    D02C                STA MULTZ
F14A A6    89 D040             LDA SEQXZ,X
F14E B7    D072                STA $D072
F151 8E    F8EE      RTN       LDX #$F8EE     RETURN TO STANDBY MODE
F154 AF    6A                  STX $0A,S
F156 20    1A                  BRA RTNVT1
F158 8E    F900      GO        LDX #$F900     RETURN TO START
F15B AF    6A                  STX $0A,S
F15D 20    13                  BRA RTNVT1
F15F 8E    FD2A      CONTUE LDX #$FD2A
F162 AF    6A                  STX $0A,S
F164 20    0C                  BRA RTNVT1
F166 8E    F8B7      RTNH      LDX #$F8B7        RETURN TO HOME MODE
F169 AF    6A                  STX $0A,S
F16B 20    05                  BRA RTNVT1
F16D 86    C0        RTNVT     LDA #%11000000
F16F B7    8000                STA PIA1DA
F172 86    07        RTNVT1 LDA #%00000111      ENABLE KEYBOARD INTERRUPT
F174 B7    8001                STA PIA1CA
F177 3B                        RTI
                     *
                     *
                     ******************************************************
                     *                                                    *
                     *    MOVEMENT IN X DIRECTION                         *
                     *    THIS ROUTINE ALLOWS THE X DISPLACEMENT          *
                     *    OF THE MANIPULATOR TO BE ENTERED VIA            *
                     *    KEYBOARD WITH M.S.D. FIRST. THE DIGITS ARE      *
                     *    DISPLAYED AS ENTERED. ANY ERROR MADE IN         *
                     *    THE ENTRY CAN BE CORRECTED BY REENTERING        *
                     *    THE DIGITS AGAIN. IF NO ERROR IS MADE THEN      *
                     *    THE DIGITS ARE TRANSFERRED FOR STORAGE          *
                     *    AND FURTHER CALCULATION.                        *
                     *                                                    *
```

```
                   **************************************************
                   *
                   *
F178 4F            INPUTX CLRA
F179 C6   04              LDB #4
F17B 8E   0000            LDX #0
F17E A7   89 D010  CONTX  STA BUFF1,X      CLEAR X BUFFER
F182 30   01              LEAX 1,X
F184 5A                   DECB
F185 26   F7              BNE CONTX
F187 BD   F68F            JSR DISPXY        CLEAR X DISPLAY
F18A C6   04              LDB #4
F18C 8E   0003            LDX #3
F18F BD   F6A9     KXWAIT JSR READK
F192 A7   89 D010         STA BUFF1,X
F196 30   1F              LEAX -1,X
F198 BD   F68F            JSR DISPXY        DISPLAY DIGIT
F19B 5A                   DECB
F19C 26   F1              BNE KXWAIT
                   *
F19E BD   F6A9     FXWAIT JSR READK        IS KEY PRESSED = F
F1A1 81   0E              CMPA #$0E
F1A3 26   F9              BNE FXWAIT          NO SCAN AGAIN
                   *
F1A5 BD   F6A9     EXWAIT JSR READK
F1A8 81   0A              CMPA #$0A
F1AA 27   06              BEQ ENTERX
F1AC 81   0B              CMPA #$0B
F1AE 27   C8              BEQ INPUTX          IS KEY PRESSED = CANCEL
F1B0 20   F3              BRA EXWAIT          YES ENTER DATA AGAIN
                   *
F1B2 C6   04       ENTERX LDB #4
F1B4 8E   0000            LDX #0
F1B7 A6   89 D010  TRANSX LDA BUFF1,X
```

```
F1BB A7    89 D000          STA DIGT1,X
F1BF 30    01               LEAX 1,X
F1C1 5A                     DECB
F1C2 26    F3               BNE TRANSX
                   *
F1C4 BD    F6FD             JSR DISPL1          DISPLAY X Y
                   *
                   *
                   ************************************************
                   *                                              *
                   *   CONVERT THE REQUIRED DISPLACEMENT TO No. OF *
                   *   STEPS AND STORE IN MEMORY LOCATION NUMBX.  *
                   *   CALCULATE THE DIRECTION OF ROTATION OF THE *
                   *   MOTOR X ( COMPARE PRESENT CONVERTED NUMBER *
                   *   WITH PREVIOUS NUMBER (NUMBXB)). IF THE     *
                   *   PRESENT NUMBER IS GREATER THEN THE PREVIOUS *
                   *   NUMBER THEN GIVE MOTOR CLOCKWISE ROTATION, *
                   *   IF LESS THEN - GIVE MOTOR COUNTER CLOCKWISE *
                   *   ROTATION .                                 *
                   *                                              *
                   ************************************************
                   *
                   *
F1C7 8E    0001             LDX #1
F1CA 108E  0000             LDY #0
F1CE BD    F625             JSR RCONVT
F1D1 F6    D03F             LDB COUNT
F1D4 F7    D053             STB STEPX
F1D7 F1    D032             CMPB VTUL0X
F1DA 22    4A               BHI CONXF
                   *
                   *                                              *
                   ************************************************
                   *
```

```
                    *   COUNTER CLOCKWISE MOTOR X ROTATION ROUTINE    *
                    *   THIS ROUTINE CALCULATES THE NUMBER OF STEPS   *
                    *   TO BE TAKEN IN THE COUNTER CLOCKWISE          *
                    *   DIRECTION . IF THE NUMBER OF STEPS IS GREATER*
                    *   THAN 10 THE MOTOR GOES INTO RAMP MODE AND     *
                    *   FOR STEPS LESS THAN 10 THE MOTOR GOES INTO    *
                    *   CONSTANT SPEED MODE.                          *
                    *                                                 *
                    ***************************************************
                    *
                    *
F1DC F6    D032            LDB VTUL0X
F1DF F0    D053            SUBB STEPX
F1E2 5C                    INCB
F1E3 F7    D026            STB NUMBX
F1E6 F6    D026            LDB NUMBX
F1E9 C1    0A              CMPB #10
F1EB 22    1A              BHI KRMPXR
                    *
                    *
                    ************************************************
                    *                                              *
                    *    CONSTANT SPEED MODE. IN THIS MODE THE     *
                    *    MOTOR STEPS AT A CONSTANT SPEED OF 2STEPS/ *
                    *    SECOND IN THE COUNTER CLOCKWISE DIRECTION. *
                    *                                              *
                    ************************************************
                    *
                    *
F1ED BE    D069     CONTXR LDX NUMX
F1F0 BD    F790     STXCCW JSR SEQXKC
F1F3 7A    D026            DEC NUMBX     IS NO. OF STEPS TO BE TAKEN = 0
F1F6 27    7A              BEQ RTNXB     YES RETURN
F1F8 30    01       CSTXR  LEAX 1,X
```

```
F1FA BF   D069            STX NUMX
F1FD 8C   0004            CMPX #4
F200 26   EE              BNE STXCCW
F202 BD   F733            JSR SETXB
F205 20   E6              BRA CONTXR
                   *
                   *
                   ***********************************************
                   *                                             *
                   *    RAMP MODE. IN THIS MODE THE MOTOR        *
                   *    ACCELERATES FROM 2 STEPS/SEC TO 15 STEPS/*
                   *    SECOND AND DECELERATES TO 2 STEPS/SEC    *
                   *    FOR THE LAST 5 STEPS. THIS ENSURES NO    *
                   *    OVER SHOOT AT THE END OF THE SEQ. OR NO  *
                   *    STEPS MISSED AT THE START OF THE SEQ.    *
                   *    AND ALSO REACHING THE DESIRED POSITION   *
                   *    QUICKLY.                                 *
                   *                                             *
                   ***********************************************
                   *
                   *
F207 7F   D050     KRMPXR CLR COUNTR
F20A BE   D069     KCNTXR LDX NUMX
F20D BD   F79E     KSXCCW JSR SEQXKR
F210 F6   D026            LDB NUMBX
F213 C1   05              CMPB #5
F215 27   E1              BEQ CSTXR
F217 30   01              LEAX 1,X
F219 BF   D069            STX NUMX
F21C 8C   0004            CMPX #4
F21F 26   EC              BNE KSXCCW
F221 BD   F733            JSR SETXB
F224 20   E4              BRA KCNTXR
                   *
```

```
                         *
                         *************************************************
                         *                                               *
                         *    CLOCKWISE STEPPING SEQUENCE - MOTOR X      *
                         *                                               *
                         *************************************************
                         *
                         *
F226 F0   D032           CONXF  SUBB VTULOX
F229 5C                         INCB
F22A F7   D026                  STB NUMBX
F22D F6   D026                  LDB NUMBX
F230 C1   0A                    CMPB #10
F232 22   1A                    BHI KRMPXF
                         *
                         *
                         *************************************************
                         *                                               *
                         *    CONSTANT SPEED MODE. THE MOTOR X STEPS     *
                         *    AT A CONSTANT SPEED OF 2 STEPS/SEC.        *
                         *                                               *
                         *************************************************
                         *
                         *
F234 BE   D069           CONTXF LDX NUMX    ENABLE MOTOR IN CW DIRECTION
F237 BD   F790           STXCW  JSR SEQXKC
F23A 7A   D026                  DEC NUMBX          IS NO. OF STEPS = 0
F23D 27   2E                    BEQ RTNXA          YES  RETURN
F23F 30   1F             CSTXF  LEAX -1,X
F241 BF   D069                  STX NUMX
F244 8C   FFFF                  CMPX #-1
F247 26   EE                    BNE STXCW          NO CONTINUE SEQ.
F249 BD   F738                  JSR SETXA
F24C 20   E6                    BRA CONTXF
```

```
                   *
                   *
                   **********************************************
                   *                                            *
                   *    RAMP MODE. IN THIS MODE THE MOTOR X     *
                   *    ACCELERATES FROM 2 STEPS/SEC TO 15 STEPS*
                   *    /SEC AND DECELERATES TO 2 STEPS/SEC FOR *
                   *    THE LAST 5 STEPS.                       *
                   *                                            *
                   **********************************************
                   *
                   *
F24E 7F   D050     KRMPXF CLR COUNTR
F251 BE   D069     KCNTXF LDX NUMX
F254 BD   F79E     KSXCW  JSR SEQXKR
F257 F6   D026            LDB NUMBX
F25A C1   05              CMPB #5
F25C 27   E1              BEQ CSTXF
F25E 30   1F              LEAX -1,X
F260 BF   D069            STX NUMX
F263 8C   FFFF            CMPX #-1
F266 26   EC              BNE KSXCW
F268 BD   F738            JSR SETXA
F26B 20   E4              BRA KCNTXF
                   *
F26D BD   F7C8     RTNXA  JSR MOTOA
F270 20   03              BRA RTNX
F272 BD   F7DD     RTNXB  JSR MOTOB
F275 B6   D053     RTNX   LDA STEPX     UPDATE MOTOR X DIRECTION
F278 B7   D032            STA VTUL0X      REG. , DISP. REF. REG.
F27B B7   D02A            STA MULTX       AND SEQ. REGISTER
F27E 16   FED0            LBRA RTN
                   *
                   *
                   ***********************************************
                   *                                             *
                   *      MOVEMENT IN Y DIRECTION                *
                   *      THE ROUTINE ALLOWS THE Y DISPLACEMENT  *
                   *      OF THE MANIPULATOR TO BE ENTERED VIA   *
                   *     KEYBOARD WITH M.S.D. FIRST. THE DIGITS  *
                   *     ARE DISPLAYED AS ENTERED AND ANY ERROR  *
                   *     MADE IN ENTRY CAN BE CORRECTED BY       *
                   *     REENRERING ALL 4 DIGITS .               *
                   *                                             *
                   ***********************************************
                   *
                   *
F281 4F            INPUTY CLRA
F282 C6   04              LDB #4
F284 8E   0000            LDX #0
F287 A7   89 D014  CONTY  STA BUFF5,X         CLEAR BUFFER
F28B 30   01              LEAX 1,X
F28D 5A                   DECB
F28E 26   F7              BNE CONTY
F290 BD   F68F            JSR DISPXY
F293 C6   04              LDB #4
F295 8E   0003            LDX #3
F298 BD   F6A9     KYWAIT JSR READK
F29B A7   89 D014         STA BUFF5,X
F29F 30   1F              LEAX -1,X
F2A1 BD   F68F            JSR DISPXY          DISPLAY DIGIT
F2A4 5A                   DECB
F2A5 26   F1              BNE  KYWAIT
                   *
F2A7 BD   F6A9     FYWAIT JSR READK
F2AA 81   0E              CMPA #$0E
F2AC 26   F9              BNE FYWAIT
                   *
```

```
F2AE BD   F6A9      EYWAIT JSR READK
F2B1 81   0A               CMPA #$0A
F2B3 27   06               BEQ ENTERY
F2B5 81   0B               CMPA #$0B
F2B7 27   C8               BEQ INPUTY
F2B9 20   F3               BRA EYWAIT
                    *
F2BB C6   04        ENTERY LDB #4
F2BD 8E   0000             LDX #0
F2C0 A6   89 D014   TRANSY LDA BUFF5,X
F2C4 A7   89 D004          STA DIGT5,X
F2C8 30   01               LEAX 1,X
F2CA 5A                    DECB
F2CB 26   F3               BNE TRANSY
                    *
F2CD BD   F6FD             JSR DISPL1
                    *
                    *
                    ***********************************************
                    *  CONVERT DISPLACEMENT TO NO. OF STEPS AND   *
                    *  STORE IN NUMBY . CAL. DIRECTION OF ROTATION*
                    *  OF MOTOR Y.                                *
                    *                                             *
                    ***********************************************
                    *
                    *
F2D0 8E   0005             LDX #5
F2D3 108E 0004             LDY #4
F2D7 BD   F625             JSR RCONVT
F2DA F7   D054             STB STEPY
F2DD F1   D033             CMPB VTULOY
F2E0 22   4A               BHI CONYF
                    *
                    *
```

```
                   ***********************************************
                   *                                             *
                   *  COUNTER CLOCKWISE STEPPING SEQ. FOR MOTOR Y*
                   *                                             *
                   ***********************************************
                   *
                   *
F2E2 F6   D033            LDB VTULOY
F2E5 F0   D054            SUBB STEPY
F2E8 5C                   INCB
F2E9 F7   D027            STB NUMBY
F2EC F6   D027            LDB NUMBY
F2EF C1   0A              CMPB #10
F2F1 22   1A              BHI KRMPYR
                   *
                   *
                   ***********************************************
                   *                                             *
                   *  CONSTANT SPEED STEPPING FOR MOTOR Y         *
                   *                                             *
                   ***********************************************
                   *
                   *
F2F3 BE   D067     CONTYR LDX NUMY
F2F6 BD   F771     STYCCW JSR SEQYKC
F2F9 7A   D027            DEC NUMBY
F2FC 27   7A              BEQ RTNYB
F2FE 30   01       CSTYR  LEAX 1,X
F300 BF   D067            STX NUMY
F303 8C   0004            CMPX #4
F306 26   EE              BNE STYCCW
F308 BD   F727            JSR SETYB
F30B 20   E6              BRA  CONTYR
                   *
                   *
                   **********************************************
                   *                                            *
                   *   RAMP MODE STEPPING SEQ. FOR MOTOR Y      *
                   *                                            *
                   **********************************************
                   *
                   *
F30D 7F   D050     KRMPYR CLR COUNTR
F310 BE   D067     KCNTYR LDX NUMY
F313 BD   F77F     KSYCCW JSR SEQYKR
F316 F6   D027            LDB NUMBY
F319 C1   05              CMPB #5
F31B 27   E1              BEQ CSTYR
F31D 30   01              LEAX 1,X
F31F BF   D067            STX NUMY
F322 8C   0004            CMPX #4
F325 26   EC              BNE KSYCCW
F327 BD   F727            JSR SETYB
F32A 20   E4              BRA KCNTYR
                   *
                   *
                   **********************************************
                   *                                            *
                   *   CLOCKWISE STEPPING ROUTINE FOR MOTOR Y   *
                   *                                            *
                   **********************************************
                   *
                   *
F32C F0   D033     CONYF  SUBB VTULOY
F32F 5C                   INCB
F330 F7   D027            STB NUMBY
F333 F6   D027            LDB NUMBY
F336 C1   0A              CMPB #10
```

```
F338 22    1A                BHI KRMPYF
                   *
                   *
                   **********************************************
                   *                                            *
                   *   CONSTANT SPEED STEPPING SEQ.             *
                   *                                            *
                   **********************************************
                   *
                   *
F33A BE    D067    CONTYF LDX NUMY
F33D BD    F771    STYCW  JSR SEQYKC
F340 7A    D027           DEC NUMBY   IS NO. OF STEPS TO BE TAKEN = 0
F343 27    2E             BEQ RTNYA
F345 30    1F      CSTYF  LEAX -1,X
F347 BF    D067           STX NUMY
F34A 8C    FFFF           CMPX #-1
F34D 26    EE             BNE STYCW
F34F BD    F72C           JSR SETYA
F352 20    E6             BRA CONTYF
                   *
                   *
                   **********************************************
                   *                                            *
                   *    RAMP MODE STEPPING SEQUENCE             *
                   *                                            *
                   **********************************************
                   *
                   *
F354 7F    D050    KRMPYF CLR COUNTR
F357 BE    D067    KCNTYF LDX NUMY
F35A BD    F77F    KSYCW  JSR SEQYKR
F35D F6    D027           LDB NUMBY
F360 C1    05             CMPB #5
```

```
F362 27   E1                BEQ CSTYF
F364 30   1F                LEAX -1,X
F366 BF   D067              STX NUMY
F369 8C   FFFF              CMPX #-1
F36C 26   EC                BNE KSYCW
F36E BD   F72C              JSR SETYA
F371 20   E4                BRA KCNTYF
                   *
F373 BD   FF6D     RTNYA    JSR MOTOD
F376 20   03                BRA RTNY
F378 BD   FF58     RTNYB    JSR MOTOC
F37B B6   D054     RTNY     LDA STEPY
F37E B7   D033              STA VTULOY
F381 B7   D02B              STA MULTY
F384 16   FDCA              LBRA RTN
                   *
                   *
                   ************************************************
                   *                                              *
                   * THRESHOLD VOLTAGE ENTRY ROUTINE              *
                   * THIS ROUTINE ENABLES THE MINIMUM AND MAXIMUM *
                   * THRESHOLD VOLTAGES TO BE ALTERED. THE MINIMUM*
                   * THRESHOLD VOLTAGE IS SET TO DISABLE THE      *
                   * STEPPER MOTORS X & Y AND THE MAXIMUM         *
                   * THRESHOLD VOLTAGE IS SET TO DISABLE MOTORS   *
                   * X,Y, AND Z.                                  *
                   *                                              *
                   ************************************************
                   *
                   *
F387 4F            INPVTM CLRA
F388 C6   04                LDB #4
F38A 8E   0000              LDX #0
F38D A7   89 D01C  VMIN     STA BUFF0D,X    CLEAR BUFFER
```

```
F391 30   01                LEAX 1,X
F393 5A                     DECB
F394 26   F7                BNE VMIN
F396 BD   F675              JSR DISPZV
F399 C6   04                LDB #4
F39B 8E   0003              LDX #3
F39E BD   F6A9      VMINWT  JSR READK
F3A1 A7   89 D01C           STA BUFF0D,X
F3A5 30   1F                LEAX -1,X
F3A7 BD   F675              JSR DISPZV   DISPLAY DATA
F3AA 5A                     DECB         ARE ALL 4 DIGITS ENTERED
F3AB 26   F1                BNE VMINWT   NO CONTINUE
                    *
F3AD BD   F6A9      VMINF   JSR READK
F3B0 81   0E                CMPA #$0E   IS KEY PRESSED = FUNCTION
F3B2 26   F9                BNE VMINF   NO CONTINUE
                    *
F3B4 BD   F6A9      VMINEN  JSR READK
F3B7 81   0A                CMPA #$0A   IS KEY PRESSED = ENTER
F3B9 27   06                BEQ ENTVTM
F3BB 81   0B                CMPA #$0B   NO , IS KEY PRESSED = CANCEL
F3BD 27   C8                BEQ INPVTM
F3BF 20   F3                BRA VMINEN
                    *
F3C1 BD   F5F5      ENTVTM  JSR BCDHEX  CONVERT BCD TO BINARY
F3C4 BD   F6A9      ENTVTX  JSR READK
F3C7 81   0D                CMPA #$0D
F3C9 27   10                BEQ STVTMN
F3CB 81   0E                CMPA #$0E
F3CD 26   F5                BNE ENTVTX
F3CF BD   F6A9              JSR READK
F3D2 81   0D                CMPA #$0D
F3D4 26   EE                BNE ENTVTX
F3D6 F7   D02E              STB VTHMAX
```

```
F3D9 20    03             BRA RTVT
F3DB F7    D030    STVTMN STB VTHMIN
F3DE 16    FD8C    RTVT   LBRA RTNVT
                   *
                   *
                   ***********************************************
                   *                                             *
                   * " HOME"  THIS ROUTINE  WILL ENABLE THE      *
                   * MANIPULATOR  TO GO TO ITS ORIGINAL POSITION *
                   * THE ROUTINE FIRST ENABLES THE Z MOTOR . THIS*
                   * ENSURES THE MICROELECTRODE TO COME OUT OF   *
                   * THE TISSUE AND THUS PREVENT ANY TISSUE/     *
                   * MICROELECTRODE DAMAGE. ONCE THE MICRO-      *
                   * ELECTRODE IS OUTSIDE THE TISSUE THE X AND Y *
                   * MOTORS ARE STEPPED TILL THE ORIGINAL        *
                   * POSITION IS REACHED.                        *
                   *                                             *
                   ***********************************************
                   *
                   *
F3E1 86    80      HOME   LDA #%10000000      UPDATE REF WITH 10000000
F3E3 B7    D02A           STA MULTX
F3E6 B7    D02B           STA MULTY
F3E9 B7    D02C           STA MULTZ
F3EC B7    D056           STA VTULHX
F3EF B7    D057           STA VTULHY
F3F2 B7    D058           STA VTULHZ
                   *
                   *
                   *********************************************
                   *                                           *
                   *     MOTOR Z "HOME" ROUTINE                *
                   *                                           *
                   *********************************************
```

```
                        *
                        *
F3F5 B6   D034                 LDA VTUL0Z    PRESENT POST. NUMB. IN BUFFER
F3F8 B1   D058                 CMPA VTULHZ   IS NUMBER > REF.
F3FB 22   4E                   BHI MTZCCW    YES , GIVE CCW ROTATION
F3FD 1027 0098                 LBEQ CTXMTR
F401 B6   D058                 LDA VTULHZ
F404 B0   D034                 SUBA VTUL0Z
F407 4C                        INCA
F408 B7   D028                 STA NUMBZ
F40B F6   D028                 LDB NUMBZ
F40E C1   0A                   CMPB #10
F410 22   1A                   BHI KRPZF
F412 BE   D065          COTZCW LDX NUMZ      ENABLE MOTOR IN CW DIRECTION
F415 BD   F7AF          MTZCW  JSR SEQZKC
F418 7A   D028                 DEC NUMBZ     IS NUMBER OF STEPS TO BE TAKEN =0
F41B 27   75                   BEQ CTXMT     YES GO TO X MOTOR CONTROL
F41D 30   1F            FCSTZ  LEAX -1,X
F41F BF   D065                 STX NUMZ
F422 8C   FFFF                 CMPX #-1
F425 26   EE                   BNE MTZCW
F427 BD   F744                 JSR SETZA
F42A 20   E6                   BRA COTZCW
F42C 7F   D050          KRPZF  CLR COUNTR
F42F BE   D065          KCTZF  LDX NUMZ
F432 BD   F7BA          KMTZF  JSR SEQZKR
F435 F6   D028                 LDB NUMBZ
F438 C1   05                   CMPB #5
F43A 27   E1                   BEQ FCSTZ
F43C 30   1F                   LEAX -1,X
F43E BF   D065                 STX NUMZ
F441 8C   FFFF                 CMPX #-1
F444 26   EC                   BNE KMTZF
F446 BD   F744                 JSR SETZA
```

```
F449 20    E4                BRA KCTZF
                    *
F44B B0    D058     MTZCCW SUBA VTULHZ
F44E 4C                    INCA
F44F B7    D028            STA NUMBZ
F452 F6    D028            LDB NUMBZ
F455 C1    0A              CMPB #10
F457 22    1A              BHI KRPZR
F459 BE    D065     CTZCCW LDX NUMZ      ENABLE MOTOR IN CCW DIRECTION
F45C BD    F7AF     MZCCWR JSR SEQZKC
F45F 7A    D028            DEC NUMBZ
F462 27    2E              BEQ CTXMT
F464 30    01       RCSTZ  LEAX 1,X
F466 BF    D065            STX NUMZ
F469 8C    0004            CMPX #4
F46C 26    EE              BNE MZCCWR
F46E BD    F73F            JSR SETZB
F471 20    E6              BRA CTZCCW
F473 7F    D050     KRPZR  CLR COUNTR
F476 BE    D065     KCTZR  LDX NUMZ
F479 BD    F7BA     KMTZR  JSR SEQZKR
F47C F6    D028            LDB NUMBZ
F47F C1    05              CMPB #5
F481 27    E1              BEQ RCSTZ
F483 30    01              LEAX 1,X
F485 BF    D065            STX NUMZ
F488 8C    0004            CMPX #4
F48B 26    EC              BNE KMTZR
F48D BD    F73F            JSR SETZB
F490 20    E4              BRA KCTZR
                    *
F492 A6    89 D040  CTXMT  LDA SEQXZ,X
F496 B7    D072            STA $D072
                    *
```

```
                   *
                   ***********************************************
                   *                                             *
                   *    MOTOR X "HOME" ROUTINE                   *
                   *                                             *
                   ***********************************************
                   *
                   *
F499 B6   D032     CTXMTR LDA VTULOX
F49C B1   D056            CMPA VTULHX
F49F 22   4E              BHI MTXCCW
F4A1 1027 0099            LBEQ CTYMTR
F4A5 B6   D056            LDA VTULHX
F4A8 B0   D032            SUBA VTULOX
F4AB 4C                   INCA
F4AC B7   D026            STA NUMBX
F4AF F6   D026            LDB NUMBX
F4B2 C1   0A              CMPB #10
F4B4 22   1A              BHI KRPXF
F4B6 BE   D069     COTXCW LDX NUMX       ENABLE MOTOR IN CW DIRECTION
F4B9 BD   F790     MTXCW  JSR SEQXKC
F4BC 7A   D026            DEC NUMBX      IS NUMB. OF STEPS TO BE TAKEN = 0
F4BF 27   75              BEQ CTYMTA     YES GO TO MOTOR Y CONTROL
F4C1 30   1F       FCSTX  LEAX -1,X
F4C3 BF   D069            STX NUMX
F4C6 8C   FFFF            CMPX #-1
F4C9 26   EE              BNE MTXCW
F4CB BD   F738            JSR SETXA
F4CE 20   E6              BRA COTXCW
F4D0 7F   D050     KRPXF  CLR COUNTR
F4D3 BE   D069     KCTXF  LDX NUMX
F4D6 BD   F79E     KMTXF  JSR SEQXKR
F4D9 F6   D026            LDB NUMBX
F4DC C1   05              CMPB #5
```

```
F4DE 27    E1                BEQ FCSTX
F4E0 30    1F                LEAX -1,X
F4E2 BF    D069              STX NUMX
F4E5 8C    FFFF              CMPX #-1
F4E8 26    EC                BNE KMTXF
F4EA BD    F738              JSR SETXA
F4ED 20    E4                BRA KCTXF
                    *
F4EF B0    D056     MTXCCW SUBA VTULHX
F4F2 4C                      INCA
F4F3 B7    D026              STA NUMBX
F4F6 F6    D026              LDB NUMBX
F4F9 C1    0A                CMPB #10
F4FB 22    1A                BHI KRPXR
F4FD BE    D069     CTXCCW LDX NUMX      ENABLE MOTOR IN CCW DIRECTION
F500 BD    F790     MXCCWR JSR SEQXKC
F503 7A    D026              DEC NUMBX   IS NO. OF STEPS TO BE TAKEN = 0
F506 27    33                BEQ CTYMTB  YES GO TO MOTOR Y CONTROL
F508 30    01       RCSTX    LEAX 1,X
F50A BF    D069              STX NUMX
F50D 8C    0004              CMPX #4     NO CONTINUE SEQUENCE
F510 26    EE                BNE MXCCWR
F512 BD    F733              JSR SETXB
F515 20    E6                BRA CTXCCW
F517 7F    D050     KRPXR    CLR COUNTR
F51A BE    D069     KCTXR    LDX NUMX
F51D BD    F79E     KMTXR    JSR SEQXKR
F520 F6    D026              LDB NUMBX
F523 C1    05                CMPB #5
F525 27    E1                BEQ RCSTX
F527 30    01                LEAX 1,X
F529 BF    D069              STX NUMX
F52C 8C    0004              CMPX #4
F52F 26    EC                BNE KMTXR
```

```
F531 BD   F733              JSR SETXB
F534 20   E4                BRA KCTXR
                   *
F536 BD   F7C8     CTYMTA JSR MOTOA
F539 20   03                BRA CTYMTR
F53B BD   F7DD     CTYMTB JSR MOTOB
                   *
                   *
                   **********************************************
                   *                                            *
                   *    MOTOR Y "HOME" ROUTINE                  *
                   *                                            *
                   **********************************************
                   *
                   *
F53E B6   D033     CTYMTR LDA VTUL0Y
F541 B1   D057            CMPA VTULHY
F544 22   50              BHI MTYCCW
F546 1027 009D            LBEQ RTNREF
F54A B6   D057            LDA VTULHY
F54D B0   D033            SUBA VTUL0Y
F550 4C                   INCA
F551 B7   D027            STA NUMBY
F554 F6   D027            LDB NUMBY
F557 C1   0A              CMPB #10
F559 22   1C              BHI KRPYF
F55B BE   D067     COTYCW LDX NUMY        ENABLE MOTOR Y IN CW DIRECTION
F55E BD   F771     MTYCW  JSR SEQYKC
F561 7A   D027            DEC NUMBY       IS NO. OF STEPS TO BE TAKEN = 0
F564 1027 0077            LBEQ RTNRFA     YES RETURN
F568 30   1F       FCSTY  LEAX -1,X       NO CONTINUE SEQUENCE
F56A BF   D067            STX NUMY
F56D 8C   FFFF            CMPX #-1
F570 26   EC              BNE MTYCW
```

```
F572 BD   F72C          JSR SETYA
F575 20   E4            BRA COTYCW
F577 7F   D050   KRPYF  CLR COUNTR
F57A BE   D067   KCTYF  LDX NUMY
F57D BD   F77F   KMTYF  JSR SEQYKR
F580 F6   D027          LDB NUMBY
F583 C1   05            CMPB #5
F585 27   E1            BEQ FCSTY
F587 30   1F            LEAX -1,X
F589 BF   D067          STX NUMY
F58C 8C   FFFF          CMPX #-1
F58F 26   EC            BNE KMTYF
F591 BD   F72C          JSR SETYA
F594 20   E4            BRA KCTYF
                 *
F596 B0   D057   MTYCCW SUBA VTULHY
F599 4C                 INCA
F59A B7   D027          STA NUMBY
F59D F6   D027          LDB NUMBY
F5A0 C1   0A            CMPB #10
F5A2 22   1C            BHI KRPYR
F5A4 BE   D067   CTYCCW LDX NUMY       ENABLE MOTOR IN CCW DIRECTION
F5A7 BD   F771   MYCCWR JSR SEQYKC
F5AA 7A   D027          DEC NUMBY      IS NO. OF STEPS TO BE TAKEN = 0
F5AD 1027 0033          LBEQ RTNRFB    YES RETURN
F5B1 30   01     RCSTY  LEAX 1,X       NO CONTINUE SEQ.
F5B3 BF   D067          STX NUMY
F5B6 8C   0004          CMPX #4
F5B9 26   EC            BNE MYCCWR
F5BB BD   F727          JSR SETYB
F5BE 20   E4            BRA CTYCCW
F5C0 7F   D050   KRPYR  CLR COUNTR
F5C3 BE   D067   KCTYR  LDX NUMY
F5C6 BD   F77F   KMTYR  JSR SEQYKR
```

```
F5C9 F6   D027              LDB NUMBY
F5CC C1   05                CMPB #5
F5CE 27   E1                BEQ RCSTY
F5D0 30   01                LEAX 1,X
F5D2 BF   D067              STX NUMY
F5D5 8C   0004              CMPX #4
F5D8 26   EC                BNE KMTYR
F5DA BD   F727              JSR SETYB
F5DD 20   E4                BRA KCTYR
                     *
F5DF BD   FF6D       RTNRFA JSR MOTOD
F5E2 20   03                BRA RTNREF
F5E4 BD   FF58       RTNRFB JSR MOTOC
                     *
F5E7 86   80         RTNREF LDA #%10000000
F5E9 B7   D032              STA VTULOX
F5EC B7   D033              STA VTULOY
F5EF B7   D034              STA VTULOZ
F5F2 16   FB71              LBRA RTNH
                     *
                     *
                     *************************************************
                     *                                               *
                     *    SUBROUTINE  BCDBIN                         *
                     *    THIS ROUTINE  CONVERTS BCD NUMBER TO       *
                     *     BINARY EQUIVALENT  AND STORES IN MEMORY   *
                     *    LOCATION ANSVT:ANSVT+1.                    *
                     *                                               *
                     *************************************************
                     *
                     *
F5F5 8E   0002       BCDHEX LDX #2
F5F8 A6   89 D01C           LDA BUFF0D,X
F5FC 84   0F                ANDA #%00001111
```

```
F5FE C6    64               LDB #100
F600 3D                     MUL
F601 FD    D03B             STD ANSVT
F604 30    1F               LEAX -1,X
F606 A6    89 D01C          LDA BUFF0D,X
F60A 84    0F               ANDA #%00001111
F60C C6    0A               LDB #10
F60E 3D                     MUL
F60F F3    D03B             ADDD ANSVT
F612 FD    D03B             STD  ANSVT
F615 30    1F               LEAX -1,X
F617 4F                     CLRA
F618 E6    89 D01C          LDB BUFF0D,X
F61C C4    0F               ANDB #%00001111
F61E F3    D03B             ADDD ANSVT
F621 FD    D03B             STD  ANSVT
F624 39                     RTS
                   *
                   *
                   ***********************************************
                   *                                             *
                   *    SUBROUTINE   RCONVT                      *
                   *   THIS  ROUTINE CONVERTS DISPLACEMENT AT    *
                   *   THE LOAD END TO THE STEPS  TO BE TAKEN    *
                   *    BY THE STEPPER  MOTOR .                  *
                   ***********************************************
                   *
                   *
F625 A6    89 D000  RCONVT LDA DIGT1,X       GET TENS
F629 30    01               LEAX 1,X
F62B C6    0A               LDB #10
F62D 3D                     MUL
F62E EB    A9 D000          ADDB DIGT1,Y      ADD TENS TO 1'S
F632 F7    D049             STB ANSCON+1
```

```
F635 A6    89 D000          LDA DIGT1,X      GET HUNDREDS
F639 7F    D048             CLR ANSCON
F63C 30    01               LEAX 1,X
F63E C6    64               LDB #100
F640 3D                     MUL
F641 F3    D048             ADDD ANSCON      ADD TO THE PREVIOUS RESULT
F644 FD    D048             STD ANSCON
F647 A6    89 D000          LDA DIGT1,X      GET THOUSANDS
F64B C6    64               LDB #100
F64D 3D                     MUL
F64E 1F    98               TFR B,A
F650 C6    0A               LDB #10
F652 3D                     MUL
F653 F3    D048             ADDD ANSCON
F656 FD    D048             STD ANSCON
                    *
F659 C6    08       DIVIDE  LDB #8
F65B F7    D03F             STB COUNT        COUNT + 8
F65E FC    D048             LDD ANSCON       GET DIVIDEND
F661 58             DIVD    ASLB             SHIFT DIVIDEND QUOTIENT
F662 49                     ROLA
F663 B1    D02D             CMPA MULTPD      IS TRIAL SUBTRACTION SUCCESSFUL
F666 25    04               BCS CHKCNT
F668 B0    D02D             SUBA MULTPD
F66B 5C                     INCB
F66C 7A    D03F     CHKCNT  DEC COUNT
F66F 26    F0               BNE DIVD
F671 F7    D03F             STB COUNT
F674 39                     RTS
                    *
                    *
                    ****************************************
                    *                                      *
                    *    SUBROUTINE  DISPZV                *
```

```
                         *    THIS ROUTINE DISPLAYS VTH AND Z VALUES    *
                         *    STORED  IN THE BUFFER                     *
                         *                                              *
                         ************************************************
                         *
                         *
F675 36    34            DISPZV PSHU X,Y,B
F677 BD    F75E                 JSR DSPZV
F67A 108E 0000                  LDY #0
F67E C6    08                   LDB #8
F680 A6    A9 D018       NXDIZV LDA BUFF9,Y
F684 31    21                   LEAY 1,Y
F686 B7    C008                 STA DISP2
F689 5A                         DECB
F68A 26    F4                   BNE NXDIZV
F68C 37    34                   PULU X,Y,B
F68E 39                         RTS
                         *
                         *
                         **************************************************
                         *                                                *
                         *    SUBROUTINE  DISPXY                          *
                         *  THIS ROUTINE DISPLAYS  X AND Y VALUES STORED  *
                         *         IN BUFFER.                             *
                         *                                                *
                         **************************************************
                         *
                         *
F68F 36    34            DISPXY PSHU X,Y,B
F691 BD    F74B                 JSR DSPXY
F694 108E 0000                  LDY #0
F698 C6    08                   LDB #8
F69A A6    A9 D010       NXDGXY LDA BUFF1,Y
F69E 31    21                   LEAY 1,Y
```

```
F6A0 B7    C000           STA DISP1
F6A3 5A                   DECB
F6A4 26    F4             BNE NXDGXY
F6A6 37    34             PULU X,Y,B
F6A8 39                   RTS
                   *
                   *
                   ***********************************************
                   *                                             *
                   *   SUBROUTINE READK                          *
                   *   THIS ROUTINE SCANS THE KEYBOARD AND READS *
                   *   THE KEY PRESSED.                          *
                   *                                             *
                   ***********************************************
                   *
                   *
F6A9 B6    8001    READK  LDA PIA1CA        IS KEY PRESSED
F6AC 2A    FB             BPL READK         NO WAIT
F6AE B6    8000           LDA PIA1DA        YES , GET DATA
F6B1 84    0F             ANDA #%00001111   MASK MSB
F6B3 39                   RTS
                   *
                   *
                   ************************************************
                   *                                              *
                   *   SUBROUTINE  RATIO.                         *
                   *   THIS ROUTINE CALCULATES THE SLOPE OF MICRO *
                   *   ELECTRODE TRAVEL IN THE X - Y PLANE EITHER *
                   *   AS X:1 OR 1:Y .                            *
                   *                                              *
                   ************************************************
                   *
                   *
F6B4 C6    08      RATIO  LDB #8
```

```
F6B6 F7   D080            STB CONT
F6B9 FC   D078            LDD MURTIO
F6BC 58          RTO      ASLB
F6BD 49                   ROLA
F6BE B1   D074            CMPA MLRTIO
F6C1 25   04              BCS CHKCT
F6C3 B0   D074            SUBA MLRTIO
F6C6 5C                   INCB
F6C7 7A   D080   CHKCT    DEC CONT
F6CA 26   F0              BNE RTO
F6CC 48                   LSLA
F6CD B1   D074            CMPA MLRTIO
F6D0 25   01              BLO NOCHG
F6D2 5C                   INCB
F6D3 39          NOCHG    RTS
                 *
                 *
                 **************************************************
                 *                                                *
                 *     SUBROUTINE  DELY4                          *
                 *                                                *
                 **************************************************
                 *
                 *
F6D4 108E 0064   DELY4    LDY #100
F6D8 31   3F     DL4      LEAY -1,Y
F6DA 26   FC              BNE DL4
F6DC 39                   RTS
                 *
                 *
                 **************************************************
                 *                                                *
                 *    SUBROUTINE  DELY2                           *
                 *                                                *
```

```
                    ************************************************
                    *
                    *
F6DD 108E 3A98      DELY2  LDY #15000
F6E1 31   3F        DLY2   LEAY -1,Y
F6E3 26   FC               BNE DLY2
F6E5 39                    RTS
                    *
                    *
                    ***********************************************
                    *                                             *
                    *   SUBROUTINE MCOUNT                         *
                    *   THIS ROUTINE PROVIDES A VARIABLE SPEED    *
                    *   FROM 2 STEPS/SEC TO 15 STEPS/SEC.         *
                    *                                             *
                    ***********************************************
                    *
                    *
F6E6 7C   D050      MCOUNT INC COUNTR
F6E9 F6   D050             LDB COUNTR
F6EC C1   05               CMPB #5
F6EE 22   05               BHI RMP
F6F0 BD   F6DD             JSR DELY2
F6F3 20   07               BRA RMPB
F6F5 108E 2710      RMP    LDY #10000
F6F9 BD   F6E1             JSR DLY2
F6FC 39             RMPB   RTS
                    *
                    *
                    **********************************************
                    *                                            *
                    *    SUBROUTINE DISPL1                       *
                    *                                            *
                    **********************************************
```

```
                   *
                   *
F6FD BD   F74B     DISPL1 JSR DSPXY
F700 8E   0000            LDX #0
F703 C6   08              LDB #8
F705 A6   89 D000  NXDGT1 LDA DIGT1,X
F709 B7   C000            STA DISP1
F70C 30   01              LEAX 1,X
F70E 5A                   DECB
F70F 26   F4              BNE NXDGT1
F711 39                   RTS
                   *
                   *
                   **********************************************
                   *                                            *
                   *    SUBROUTINE DISPL2                       *
                   *                                            *
                   **********************************************
                   *
                   *
F712 BD   F75E     DISPL2 JSR DSPZV
F715 8E   0000     NXDGTZ LDX #0
F718 C6   08              LDB #8
F71A A6   89 D008  NXDGT2 LDA DIGT9,X
F71E B7   C008            STA DISP2
F721 30   01              LEAX 1,X
F723 5A                   DECB
F724 26   F4              BNE NXDGT2
F726 39                   RTS
                   *
                   *
                   ********************************************
                   *                                          *
                   *    SUBROUTINE SETY                       *
```

```
                        *                                           *
                        *********************************************
                        *
                        *
F727 8E    0000         SETYB  LDX #0
F72A 20    03                  BRA SETSTY
F72C 8E    0003         SETYA  LDX #3
F72F BF    D067         SETSTY STX NUMY
F732 39                        RTS
                        *
                        *
                        *********************************************
                        *                                           *
                        *    SUBROUTINE SETX                        *
                        *                                           *
                        *********************************************
                        *
                        *
F733 8E    0000         SETXB  LDX #0
F736 20    03                  BRA SETSTX
F738 8E    0003         SETXA  LDX #3
F73B BF    D069         SETSTX STX NUMX
F73E 39                        RTS
                        *
                        *
                        ********************************************
                        *                                          *
                        *   SUBRUOTINE  SETZ                       *
                        *                                          *
                        ********************************************
                        *
                        *
F73F 8E    0000         SETZB  LDX #0
F742 20    03                  BRA SETSTZ
```

```
F744 8E   0003     SETZA  LDX #3
F747 BF   D065     SETSTZ STX NUMZ
F74A 39                   RTS
                   *
                   *
                   ******************************************
                   *                                        *
                   *    SUBROUTINE DSPXY                    *
                   *                                        *
                   ******************************************
                   *
                   *
F74B B6   D072     DSPXY  LDA $D072
F74E 8A   40              ORA #%01000000
F750 B7   9002            STA PIA2DB
F753 C6   D0              LDB #%11010000
F755 F7   C000            STB DISP1
F758 84   BF              ANDA #%10111111
F75A B7   9002            STA PIA2DB
F75D 39                   RTS
                   *
                   *
                   ******************************************
                   *                                        *
                   *    SUBROUTINE DSPZV                    *
                   *                                        *
                   ******************************************
                   *
                   *
F75E B6   D072     DSPZV  LDA $D072
F761 8A   80              ORA #%10000000
F763 B7   9002            STA PIA2DB
F766 C6   D0              LDB #%11010000
F768 F7   C008            STB DISP2
```

```
F76B 84    7F                 ANDA #%01111111
F76D B7    9002               STA PIA2DB
F770 39                       RTS
                   *
                   *
                   *******************************************
                   *                                         *
                   *  SUBROUTINE SEQYKC                      *
                   *  THIS ROUTINE RROVIDES A CONSTANT       *
                   *  STEPPING SEQ. FOR MOTOR Y              *
                   *                                         *
                   *******************************************
                   *
                   *
F771 A6    89 D044 SEQYKC LDA SEQY,X
F775 BA    D071               ORA $D071
F778 B7    8002               STA PIA1DB
F77B BD    F6DD               JSR DELY2
F77E 39                       RTS
                   *
                   *
                   *******************************************
                   *                                         *
                   *   SUBROUTINE SEQYKR                     *
                   *   THIS ROUTINE PROVIDES A RAMPING       *
                   *   STEPPING SEQUENCE FOR MOTOR Y         *
                   *                                         *
                   *******************************************
                   *
                   *
F77F A6    89 D044 SEQYKR LDA SEQY,X
F783 BA    D071               ORA $D071
F786 B7    8002               STA PIA1DB
F789 BD    F6E6               JSR MCOUNT
```

```
F78C 7A    D027           DEC NUMBY
F78F 39                   RTS
                 *
                 *
                 ********************************************
                 *                                          *
                 *    SUBROUTINE SEQXKC                     *
                 *    THIS ROUTINE PROVIDES A CONSTANT      *
                 *    STEPPING SEQUENCE FOR MOTOR X         *
                 *                                          *
                 ********************************************
                 *
                 *
F790 A6    89 D040 SEQXKC LDA SEQXZ,X
F794 BA    D070           ORA $D070
F797 B7    8002           STA PIA1DB
F79A BD    F6DD           JSR DELY2
F79D 39                   RTS
                 *
                 *
                 ********************************************
                 *                                          *
                 *    SUBROUTINE SEQXKR                     *
                 *    THIS ROUTINE PROVIDES A RAMPING       *
                 *    STEPPINGSEQUENCE FOR MOTOR X          *
                 *                                          *
                 ********************************************
                 *
                 *
F79E A6    89 D040 SEQXKR LDA SEQXZ,X
F7A2 BA    D070           ORA $D070
F7A5 B7    8002           STA PIA1DB
F7A8 BD    F6E6           JSR MCOUNT
F7AB 7A    D026           DEC NUMBX
```

```
F7AE 39                  RTS
                   *
                   *
                   ******************************************
                   *                                        *
                   *    SUBROUTINE SEQZKC                   *
                   *    THIS ROUTINE PROVIDES A CONSTANT    *
                   *    STEPPING SEQUENCE FOR MOTOR Z       *
                   *                                        *
                   ******************************************
                   *
                   *
F7AF A6    89 D040 SEQZKC LDA SEQXZ,X
F7B3 B7    9002           STA PIA2DB
F7B6 BD    F6DD           JSR DELY2
F7B9 39                   RTS
                   *
                   *
                   *
                   ******************************************
                   *                                        *
                   *     SUBROUTINE SEQZKR                  *
                   *     THIS ROUTINE PROVIDES A RAMPING    *
                   *     STEPPING SEQUENCE FOR MOTOR Z      *
                   *                                        *
                   ******************************************
                   *
                   *
F7BA A6    89 D040 SEQZKR LDA SEQXZ,X
F7BE B7    9002           STA PIA2DB
F7C1 BD    F6E6           JSR MCOUNT
F7C4 7A    D028           DEC NUMBZ
F7C7 39                   RTS
                   *
                   *
                   **********************************************
                   *                                            *
                   *   SUBROUTINE MOTOA.                        *
                   *                                            *
                   **********************************************
                   *
                   *
F7C8 A6   89 D040  MOTOA  LDA SEQXZ,X
F7CC B7   D071            STA $D071
F7CF 30   1F              LEAX -1,X
F7D1 BF   D069            STX NUMX
F7D4 8C   FFFF            CMPX #-1
F7D7 26   03              BNE NXAOK
F7D9 BD   F738            JSR SETXA
F7DC 39            NXAOK  RTS
                   *
                   *
                   **********************************************
                   *                                            *
                   *    SUBROUTINE MOTOB.                       *
                   *                                            *
                   **********************************************
                   *
                   *
F7DD A6   89 D040  MOTOB  LDA SEQXZ,X
F7E1 B7   D071            STA $D071
F7E4 30   01              LEAX 1,X
F7E6 BF   D069            STX NUMX
F7E9 8C   0004            CMPX #4
F7EC 26   03              BNE NXBOK
F7EE BD   F733            JSR SETXB
F7F1 39            NXBOK  RTS
                   *
```

```
                        *
                        *
                        *****************************************
                        *                                       *
                        *     SUBROUTINE  MOTOC                 *
                        *                                       *
                        *****************************************
                        *
                        *
FF58                            ORG $FF58
FF58 A6    89 D044      MOTOC   LDA SEQY,X
FF5C B7    D070                 STA $D070
FF5F 30    01                   LEAX 1,X
FF61 BF    D067                 STX NUMY
FF64 8C    0004                 CMPX #4
FF67 26    03                   BNE NYBOK
FF69 BD    F727                 JSR SETYB
FF6C 39                 NYBOK   RTS
                        *
                        *
                        ******************************************
                        *                                        *
                        *   SUBROUTINE MOTOD.                    *
                        *                                        *
                        ******************************************
                        *
                        *
FF6D A6    89 D044      MOTOD   LDA SEQY,X
FF71 B7    D070                 STA $D070
FF74 30    1F                   LEAX -1,X
FF76 BF    D067                 STX NUMY
FF79 8C    FFFF                 CMPX #-1
FF7C 26    03                   BNE NYAOK
FF7E BD    F72C                 JSR SETYA
```

```
FF81 39         NYAOK  RTS
                *
                *
                ******************************************
                *                                        *
                *     END OF EPROM2 PROGRAMME            *
                *                                        *
                ******************************************
                *
0000            END
```